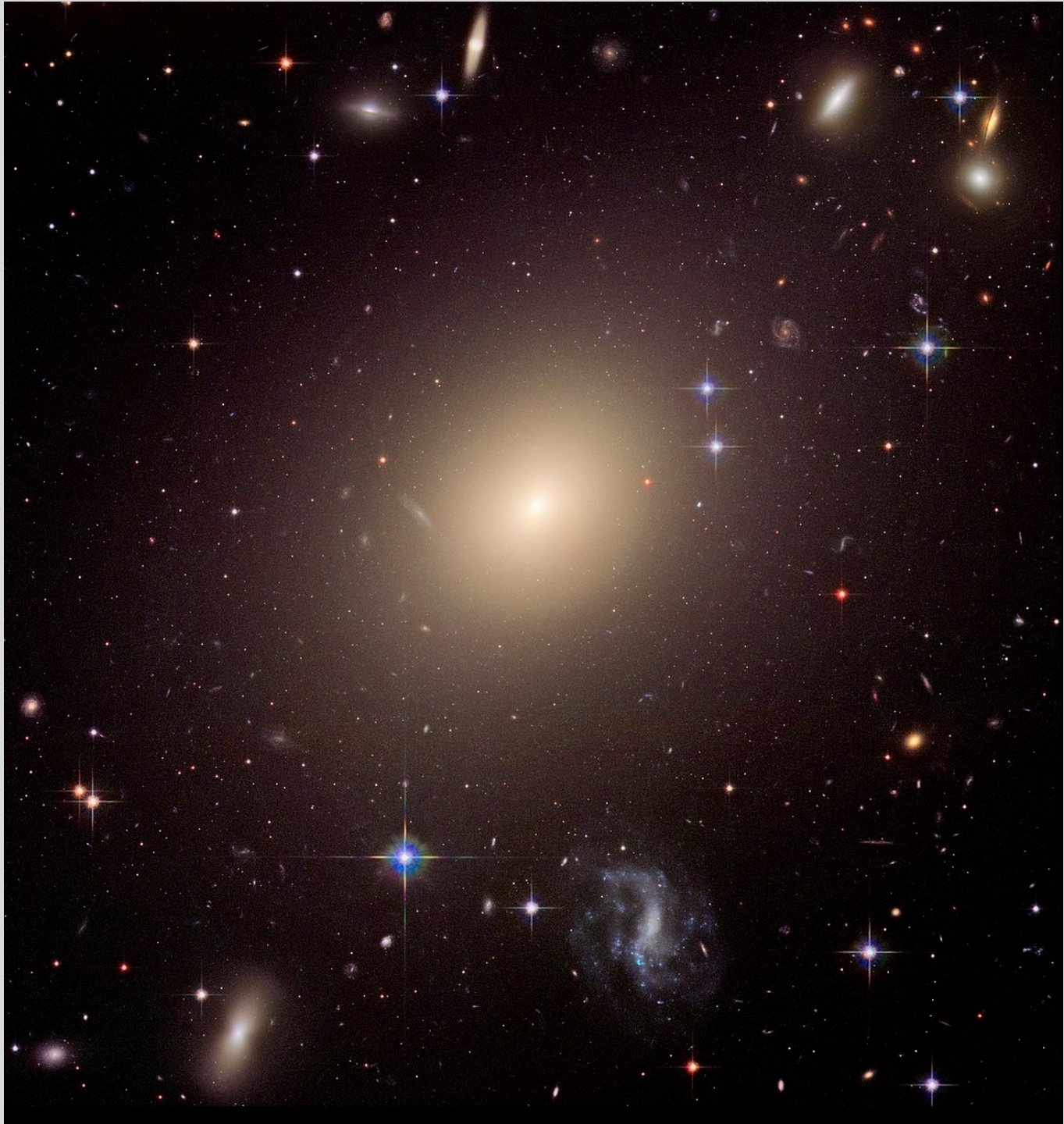
Elliptical Galaxies

E's span a wide range of luminosity and have a correspondingly wide range of structural properties.

Surface photometry: characterize

- Surface brightness profile
- Isophotal shape/ellipticity
- Orientation (position angle)
- Deviation from ellipse (boxy/disk)



Elliptical Galaxies

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isophotes: contours of constant surface brightness

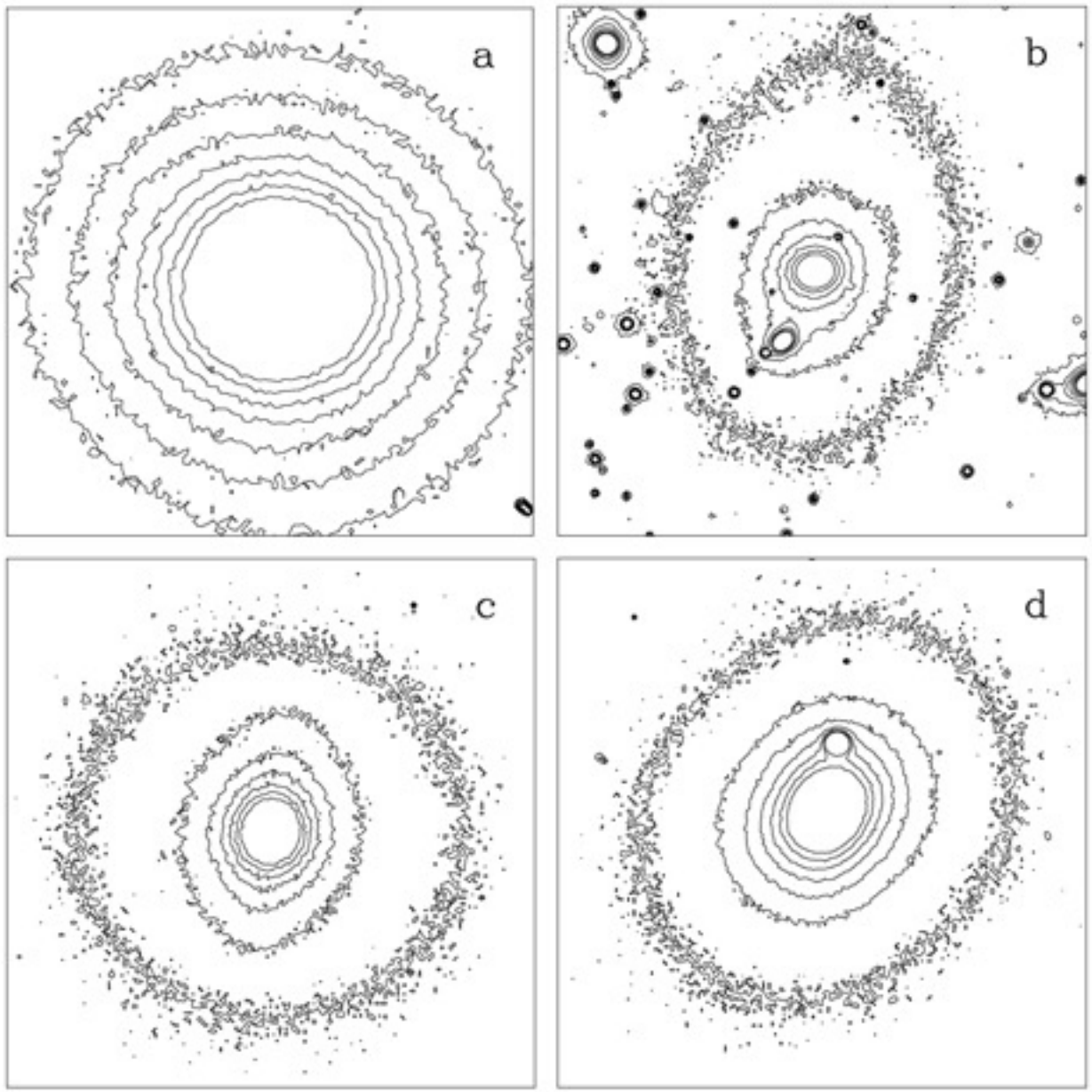


Fig 6.1 (R. de Jong) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Elliptical Galaxies: Surface Brightness profile

Characterize the surface brightness using a Sersic profile:

$$\mu(R) = \mu_e + \frac{2.5 b_n}{\ln 10}\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]$$

Where

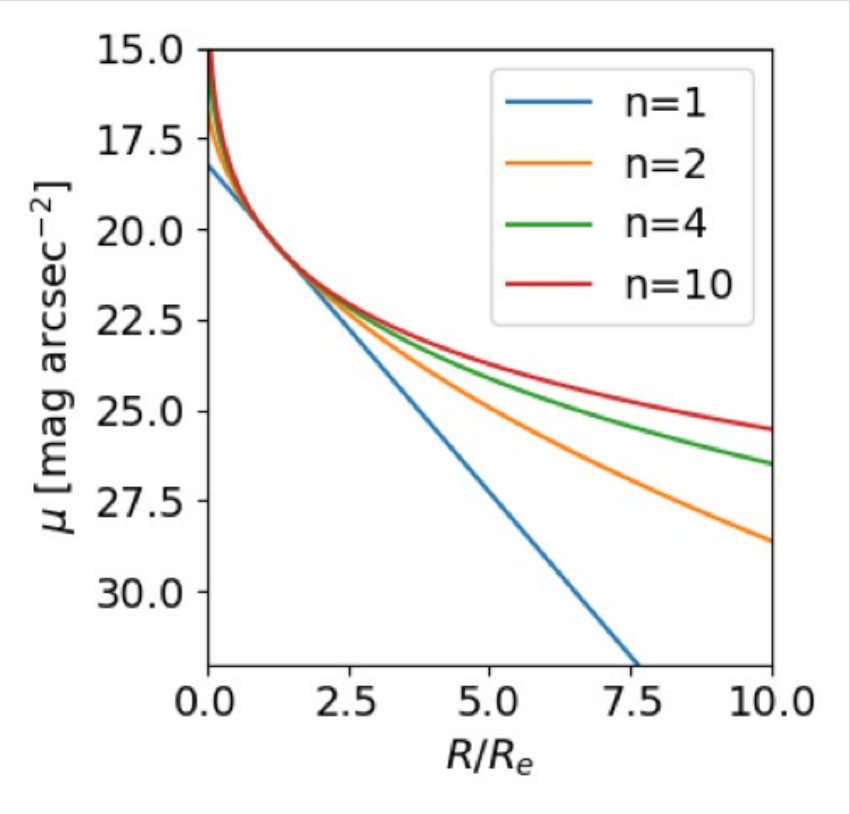
- n: Sersic index
- R_e: "effective radius", the radius containing half the total light
- μ_e: surface brightness **at** the effective radius
- (b_n: numerical constant $\approx 1.9992n - 0.3271$)

From this, we can also derive

- m: total apparent magnitude
- $\langle\mu\rangle_e$: average surface brightness **within** R_e

Remember:

- $n = 1$: exponential decline (like disk galaxies have)
- $n = 4$: classic de Vaucouleurs $r^{1/4}$ profile
- Higher n puts more and more light in the outskirts

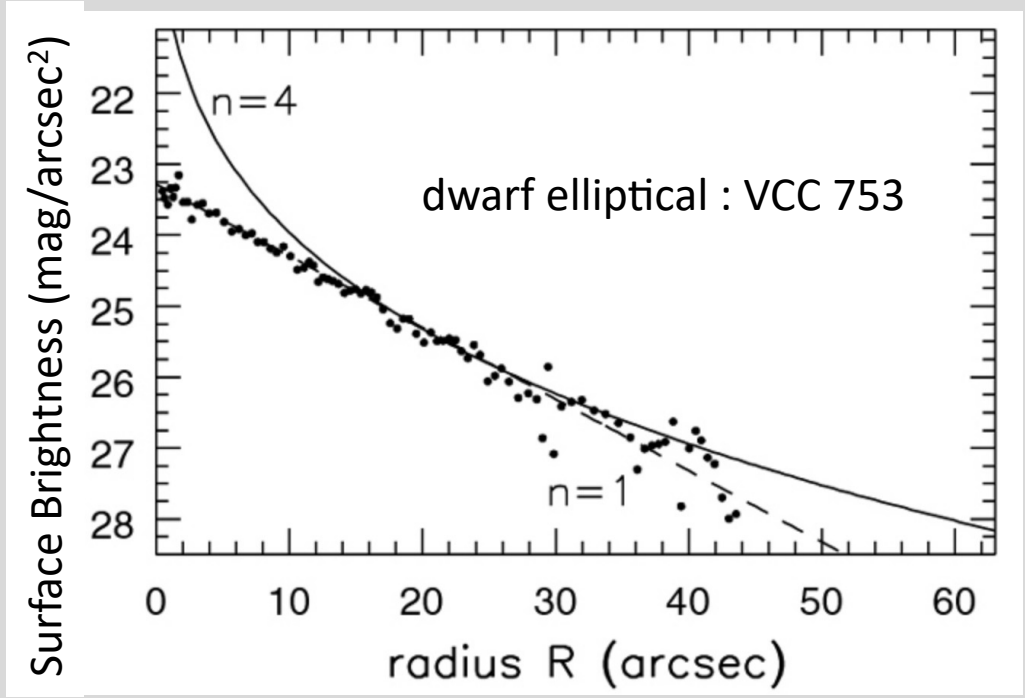


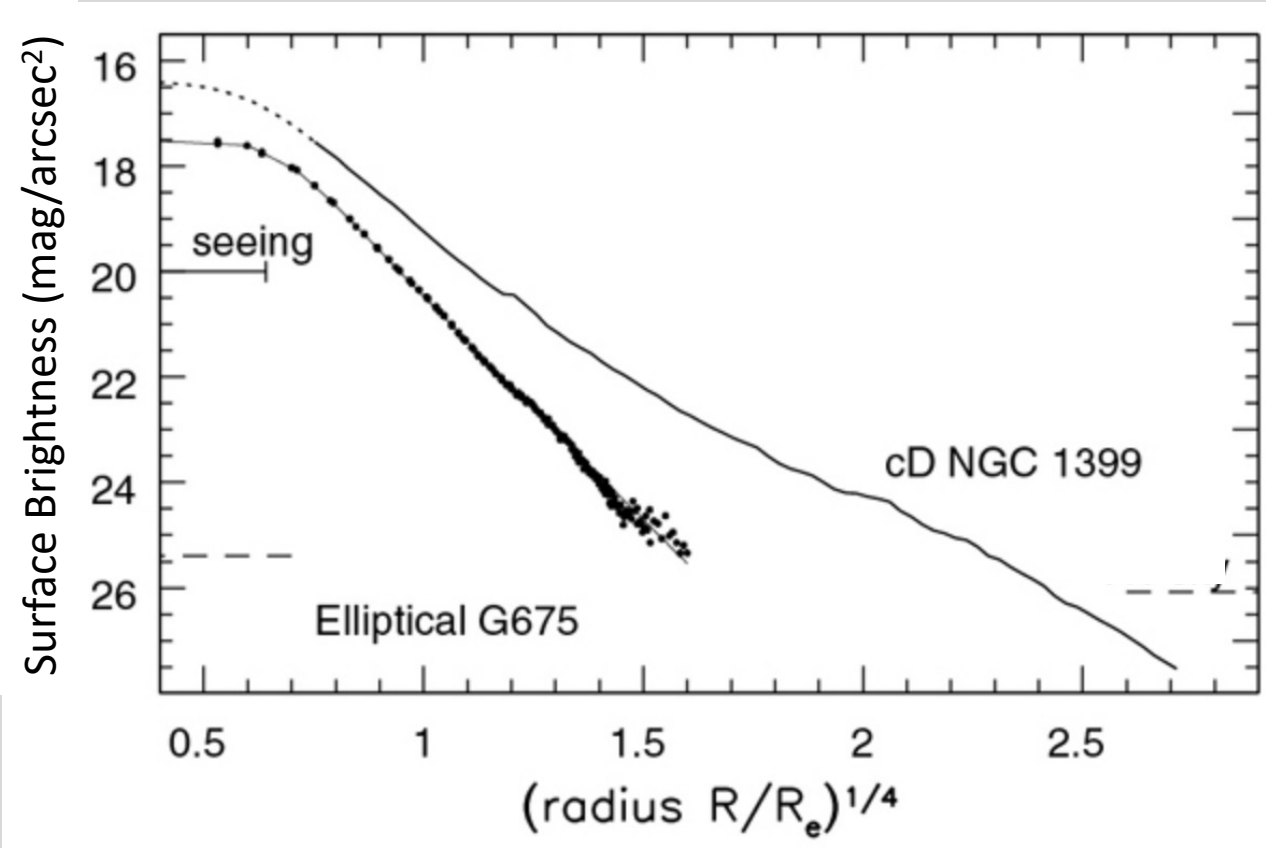
Elliptical Galaxies: Surface Brightness profile

Ellipticals are not all fit by a single value of n.

Dwarf ellipticals ($L \lesssim$ few $\times 10^9\ L_\odot$) : $n \approx 1$
(but while n=1 means an exponential profile, dE galaxies are not disk galaxies!)

Luminous ellipticals ($L\ \approx$ few $\times 10^9\ -$ few $\times 10^{10}\ L_\odot$) : $n \approx 4$





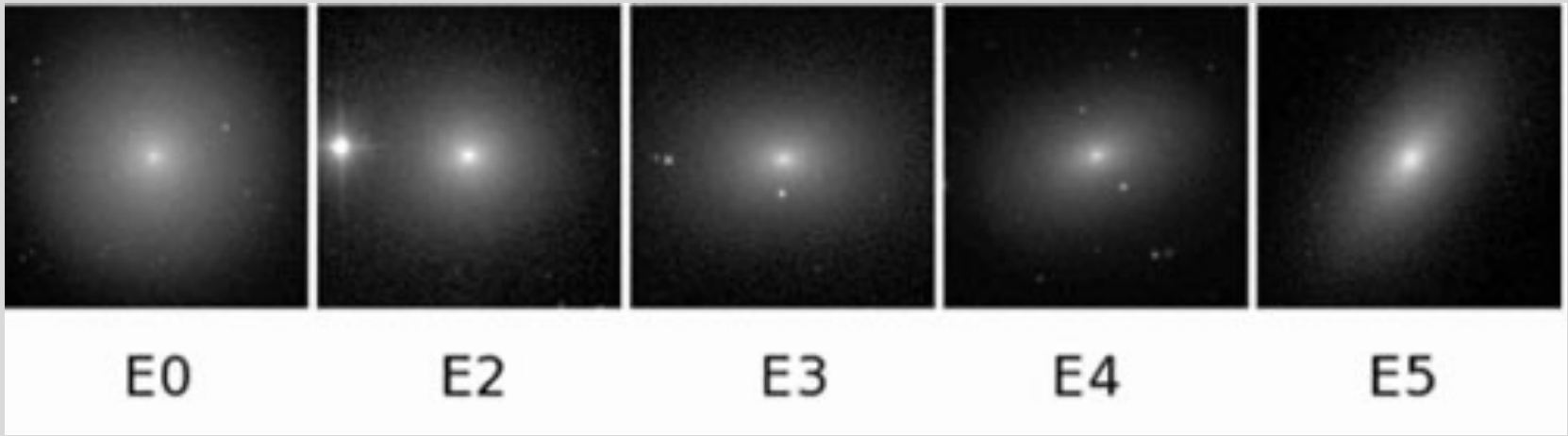
cD ("central dominant") galaxy: very luminous ellipticals at the center of big galaxy clusters.

- $L >$ few $\times 10^{10}\ L_\odot$
- Lots of excess light at large radius: $n \gg 4$
- Likely built through mergers in the cluster, with luminous envelope built from stripped galaxies.

Elliptical Galaxies: Ellipticity

Typically defined by $\epsilon = 1 - b/a$, where a, b are the isophotal major and minor axis lengths.

Hubble scheme EN, where $N = 10\epsilon$

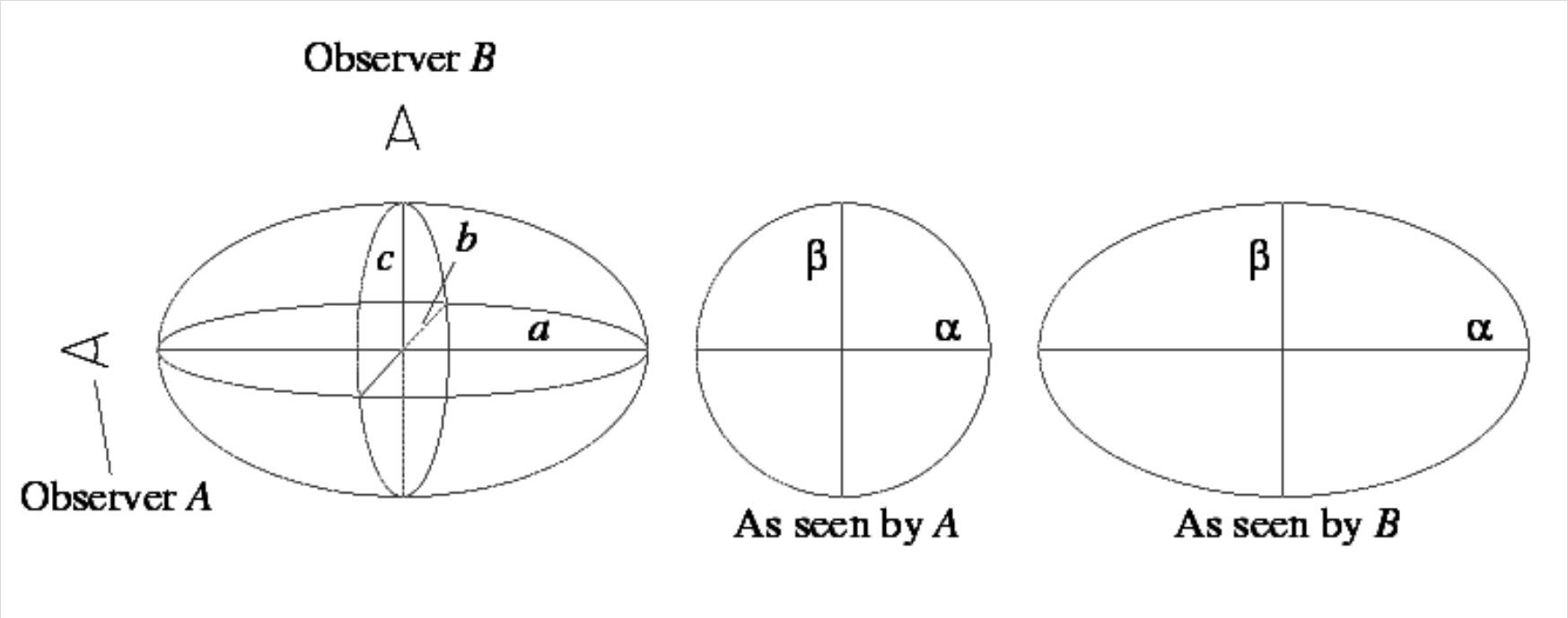


Beware: observed ellipticity is not the same as the true axis ratio.

Observed axis ratio is a projected version of the underlying 3D axis ratio.

3D geometry:

- ⚽ Spherical: $a = b = c$
- 🏈 Prolate: $a > b = c$
- 🍔 Oblate: $a = b > c$
- ?? Triaxial: $a > b > c$



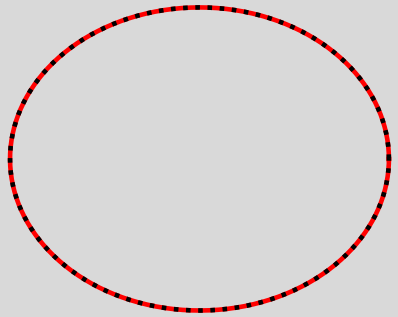
Elliptical Galaxies: Disky/Boxy

Bender+88

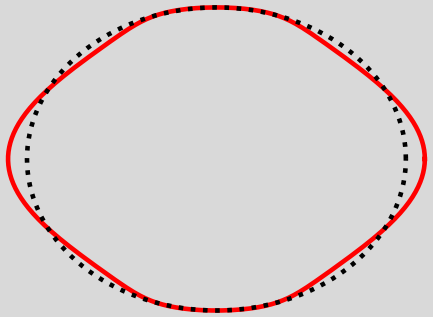
Isophotes sometimes deviate from an ellipse. We can write the deviation from a perfect ellipse as

$$\Delta r(\theta) = \sum_{k \geq 3} a_k \cos k\theta + b_k \sin k\theta$$

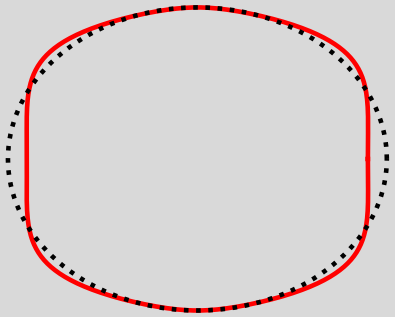
a_4: describes disky/boxy around major axis



Pure ellipse
$a_4 = 0$

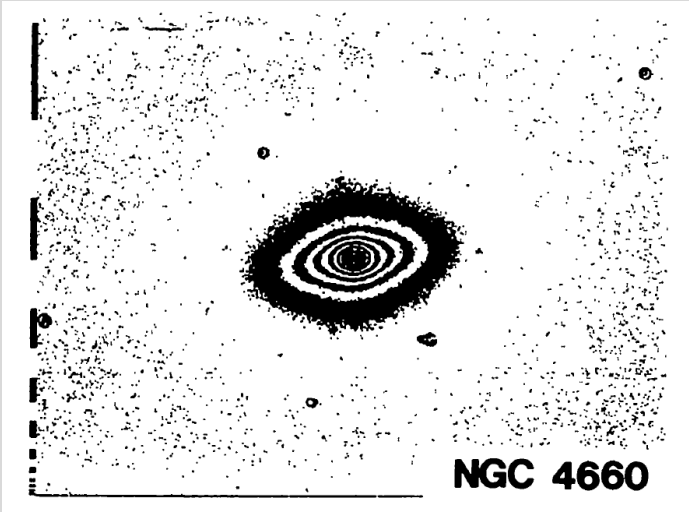


Disky isophotes
$a_4 = +0.1$

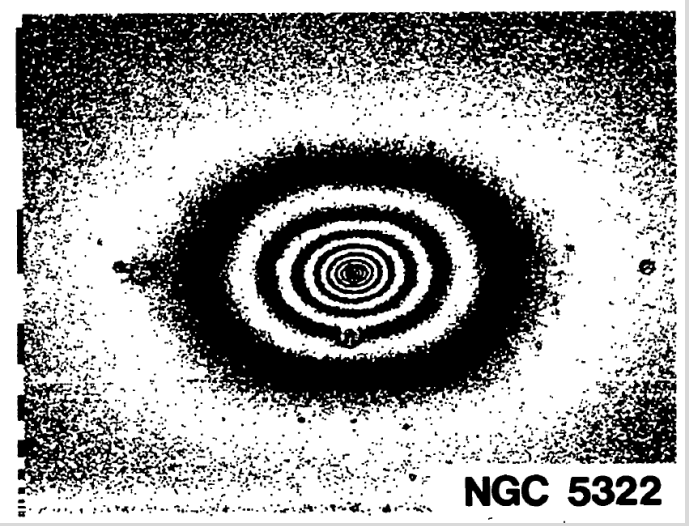


Boxy isophotes
$a_4 = -0.1$

disky

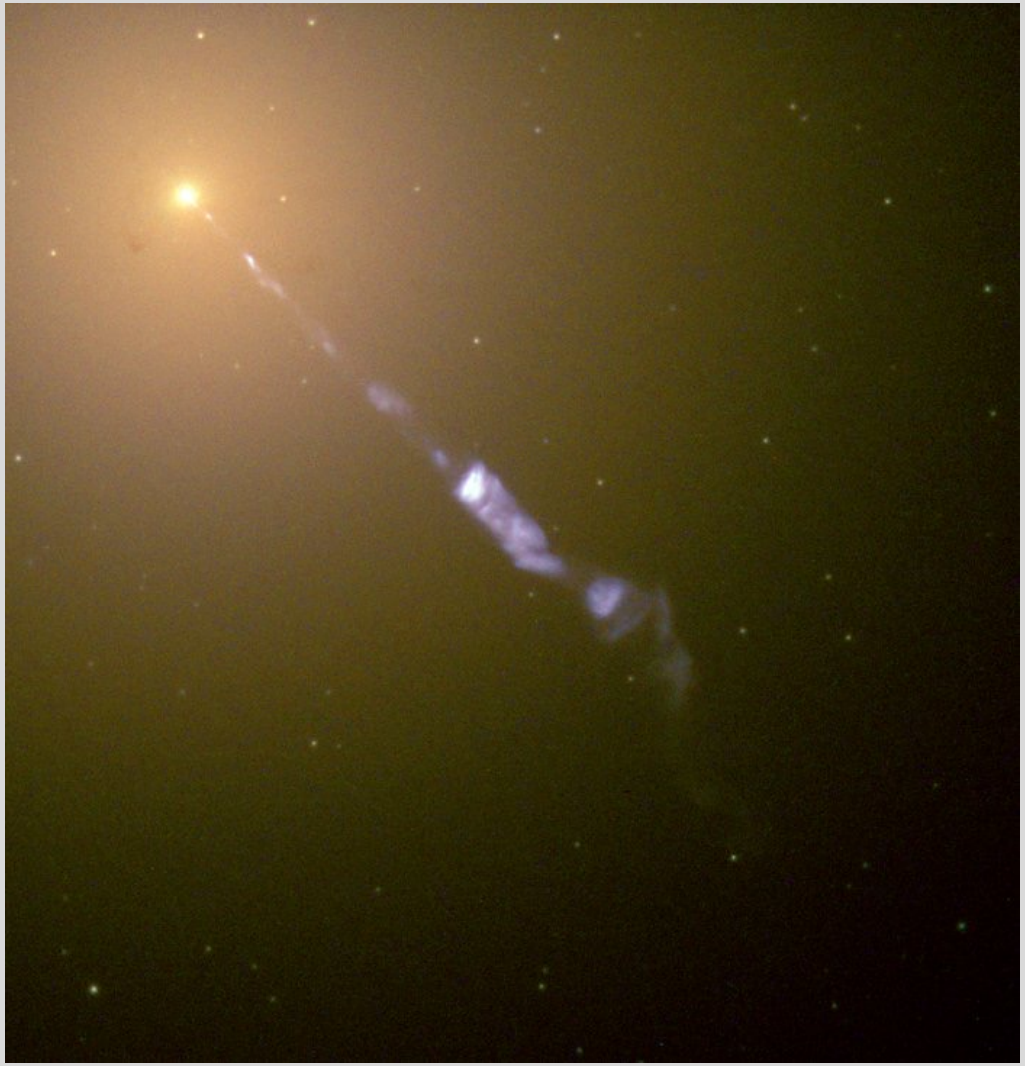


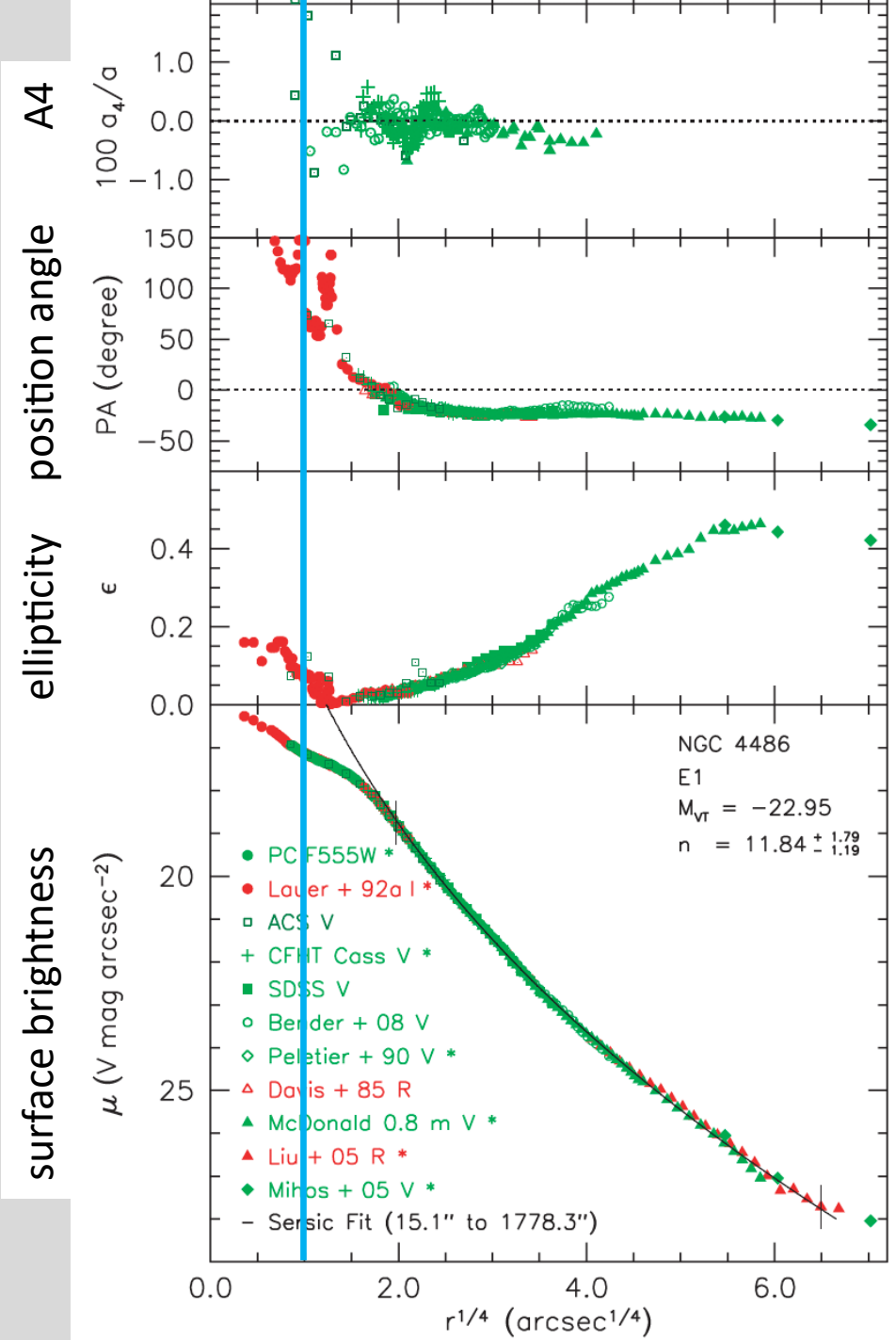
boxy



Isophotal Analysis: M87

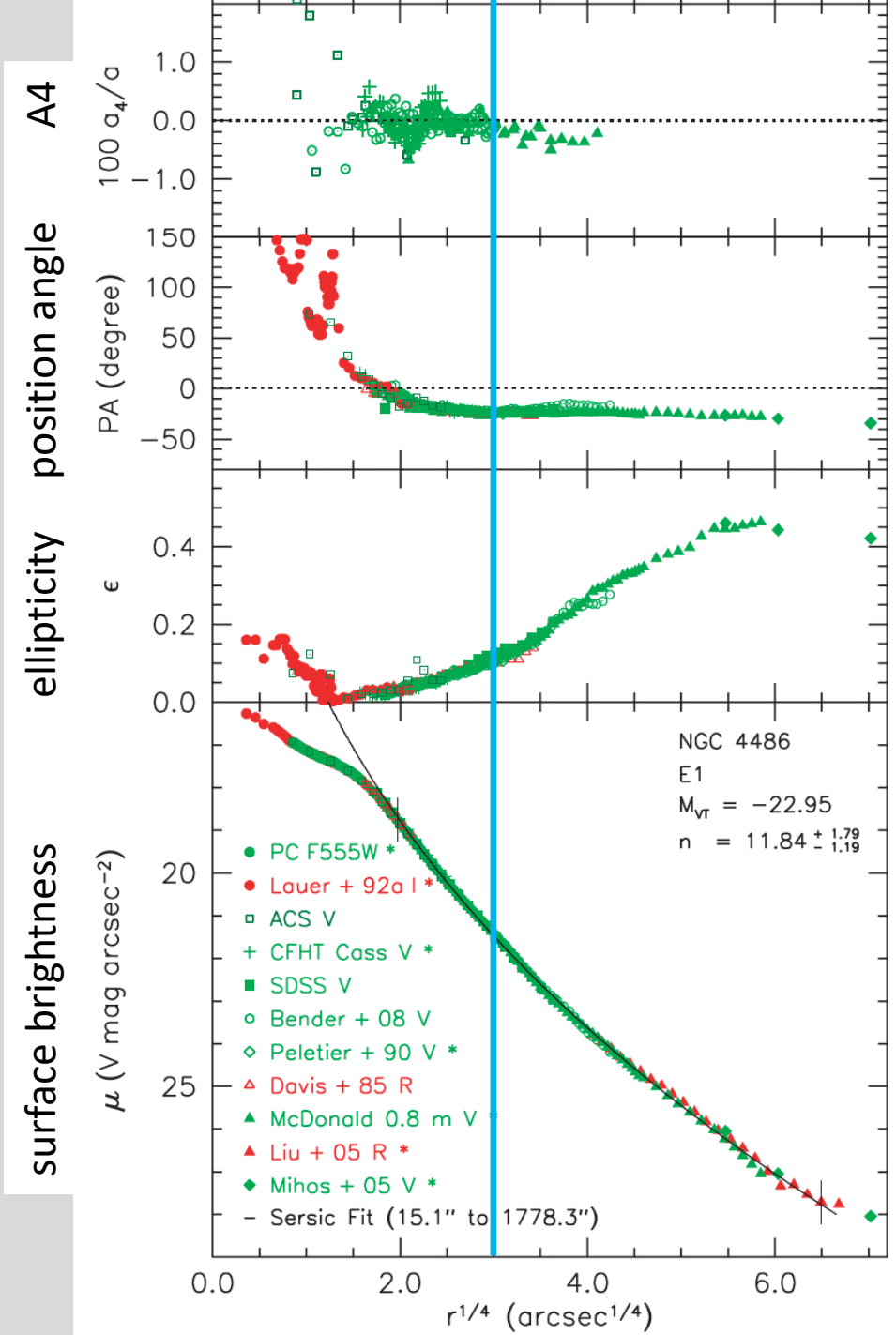
HST Image





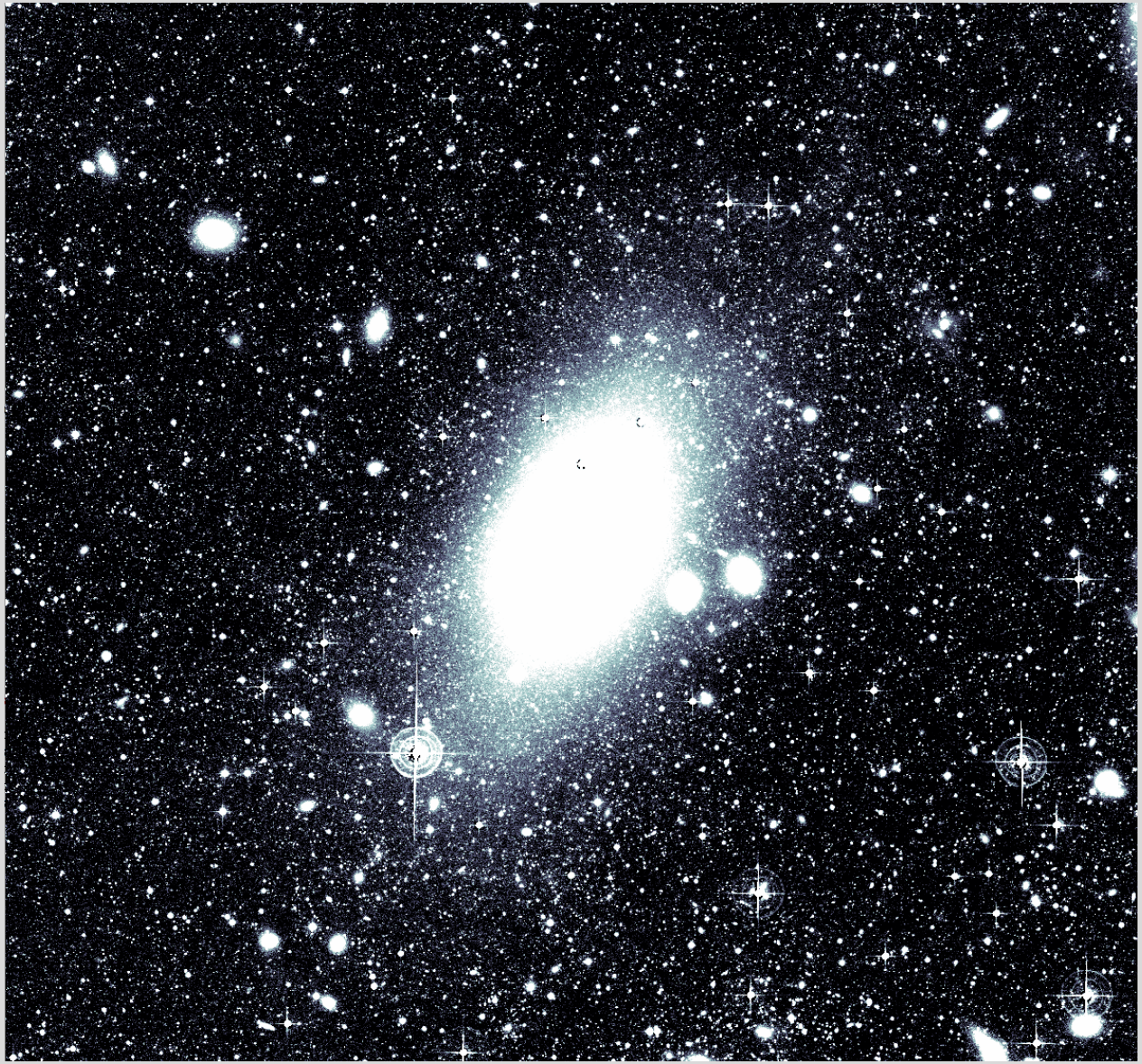
Isophotal Analysis: M87

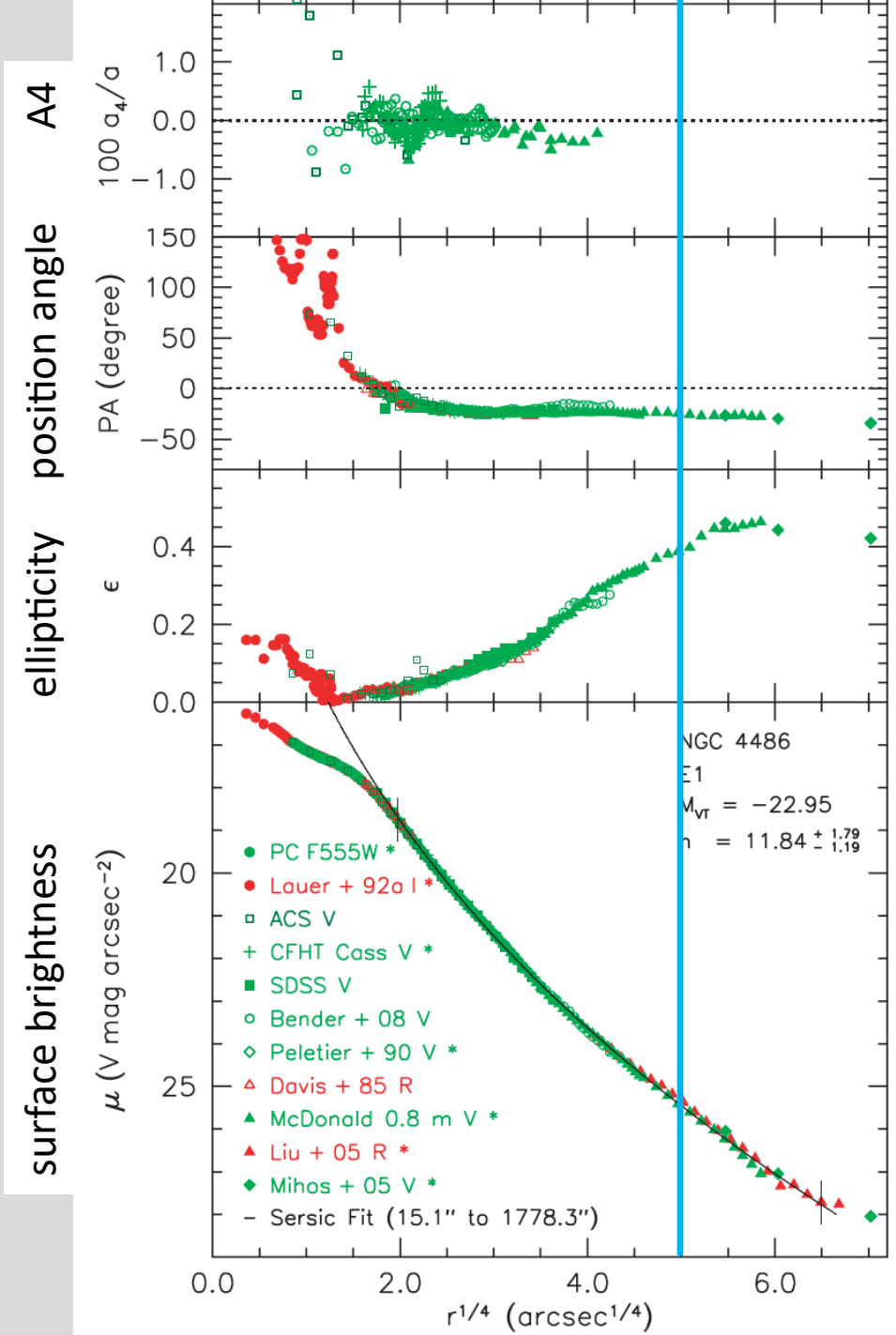
CWRU Schmidt Image



Isophotal Analysis: M87

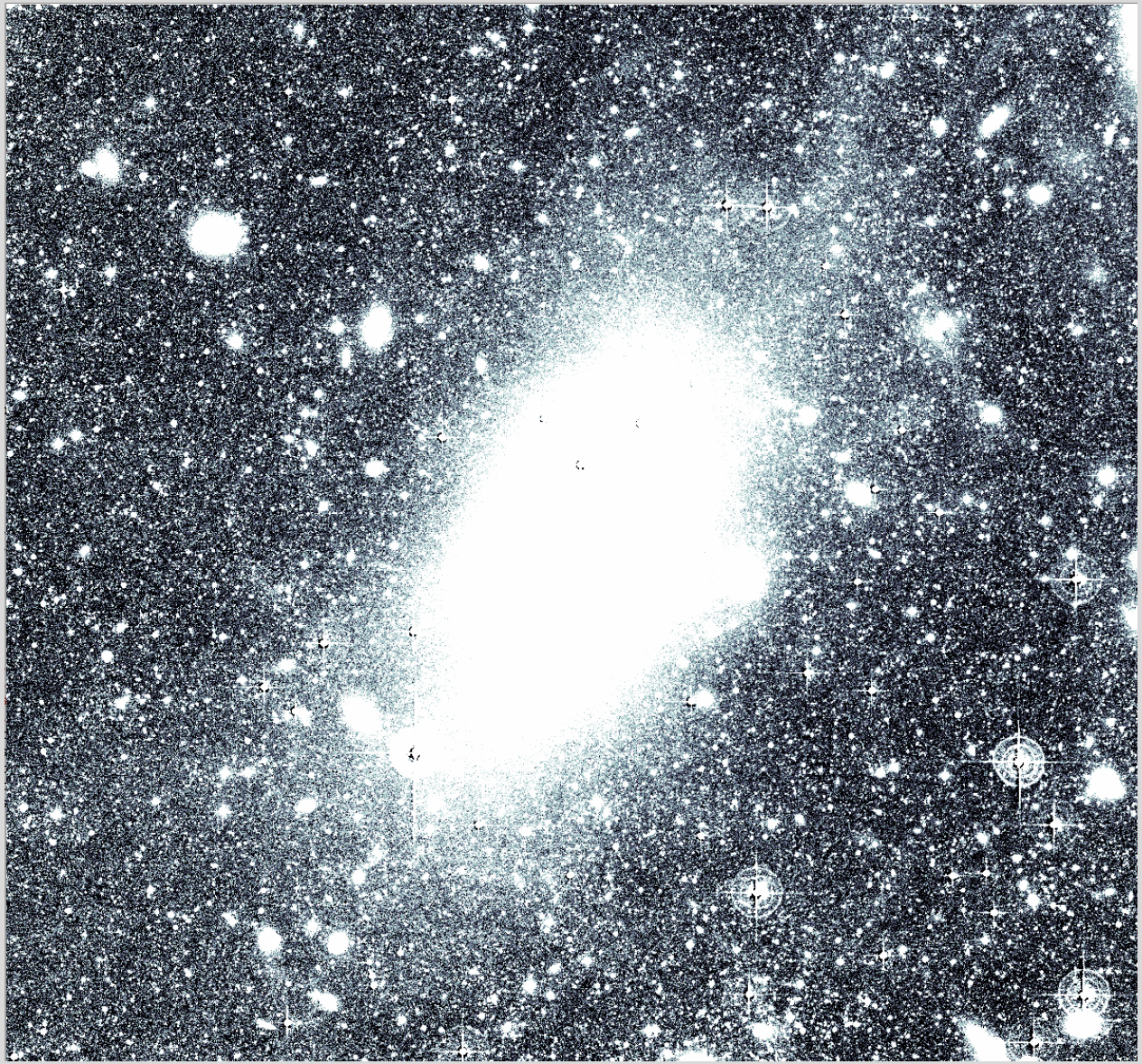
CWRU Schmidt Image

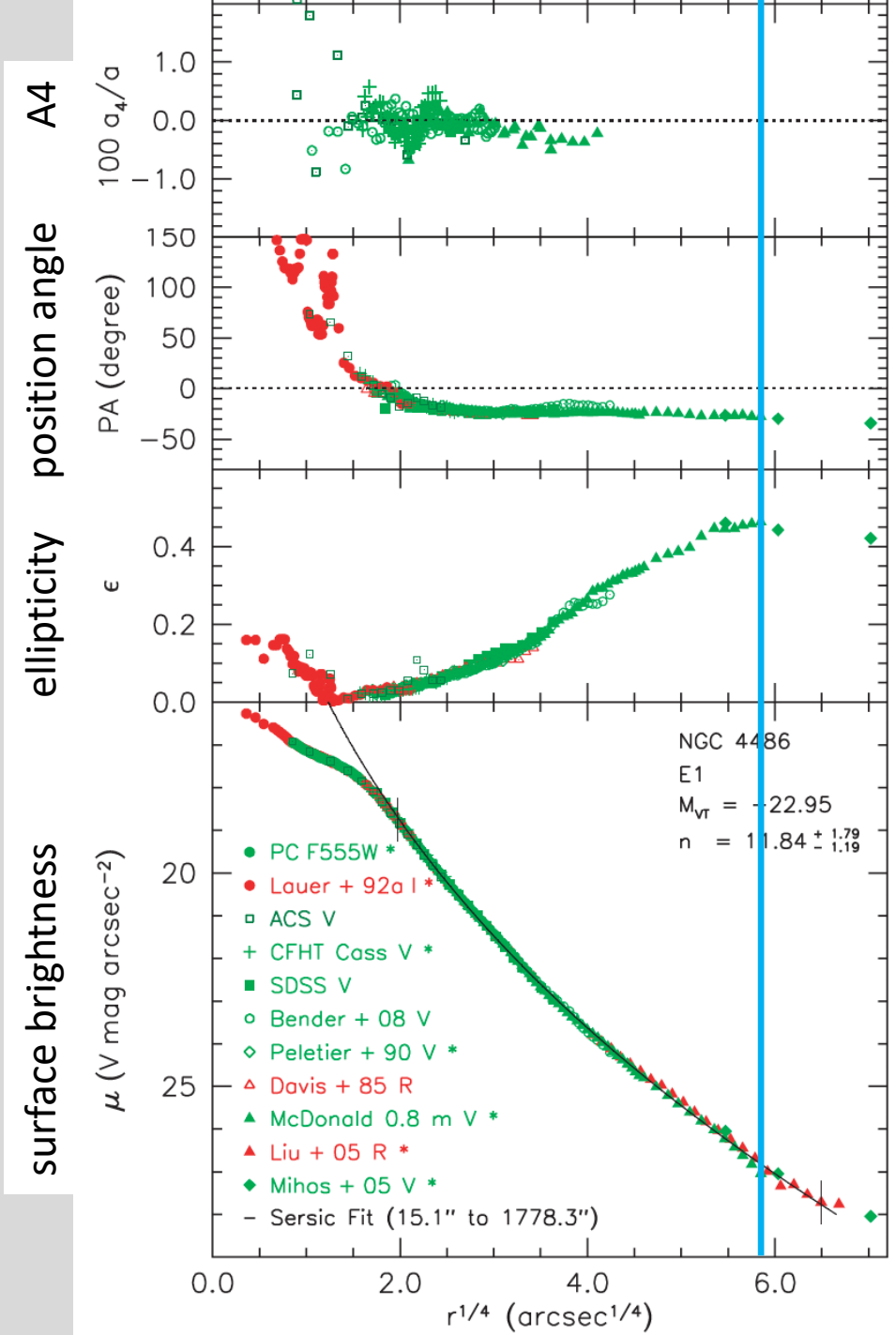




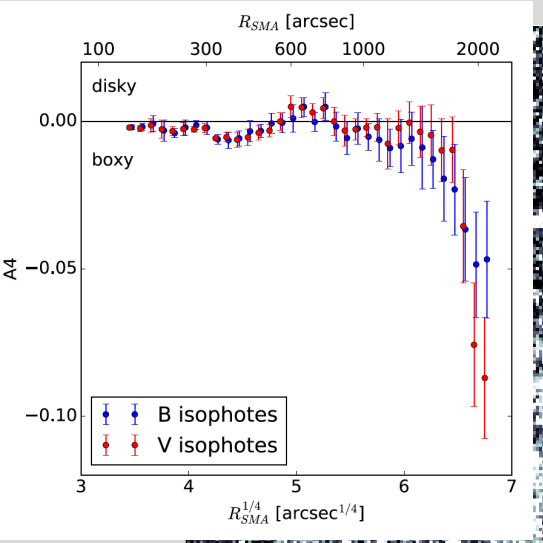
Isophotal Analysis: M87

CWRU Schmidt Image

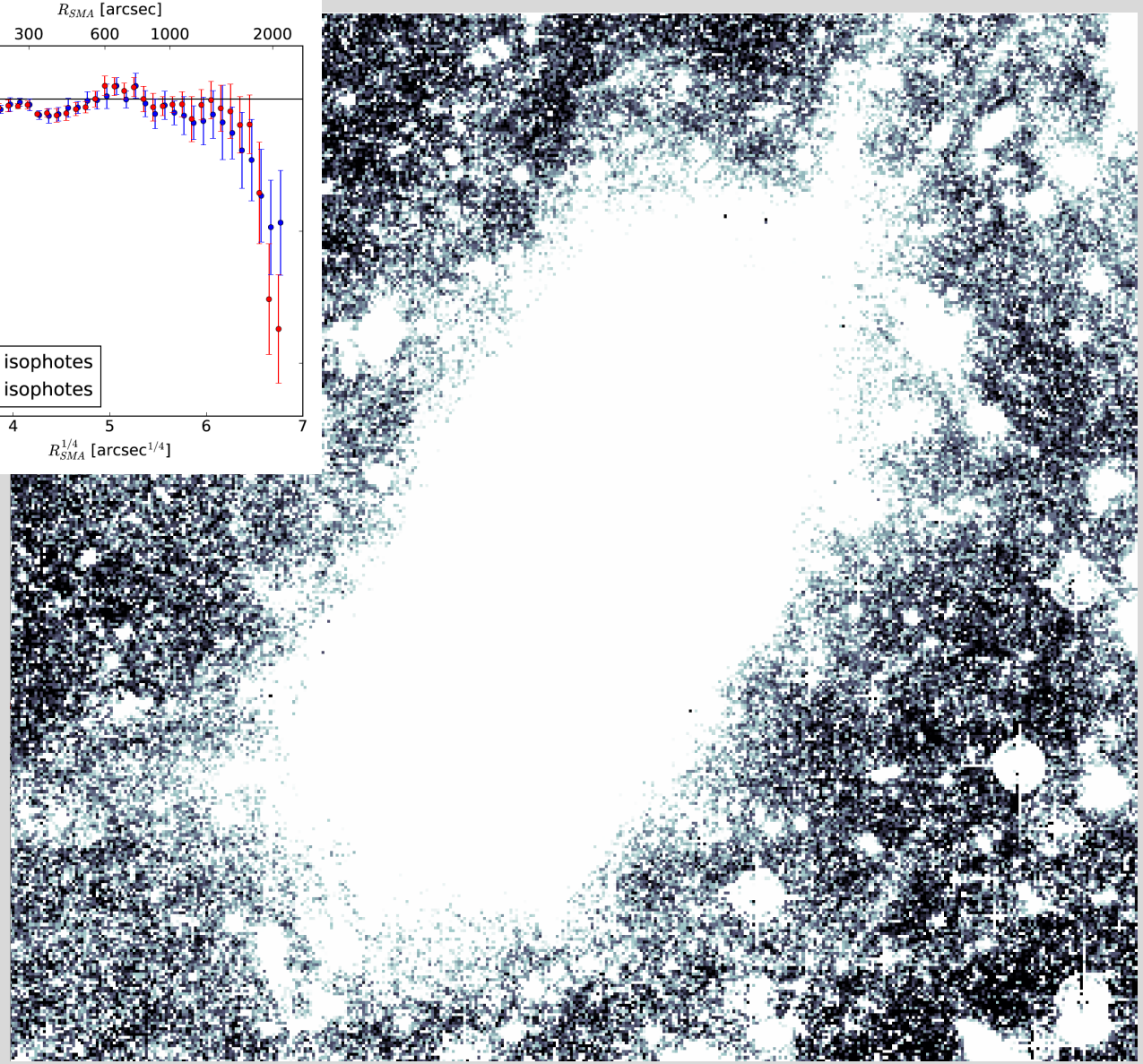


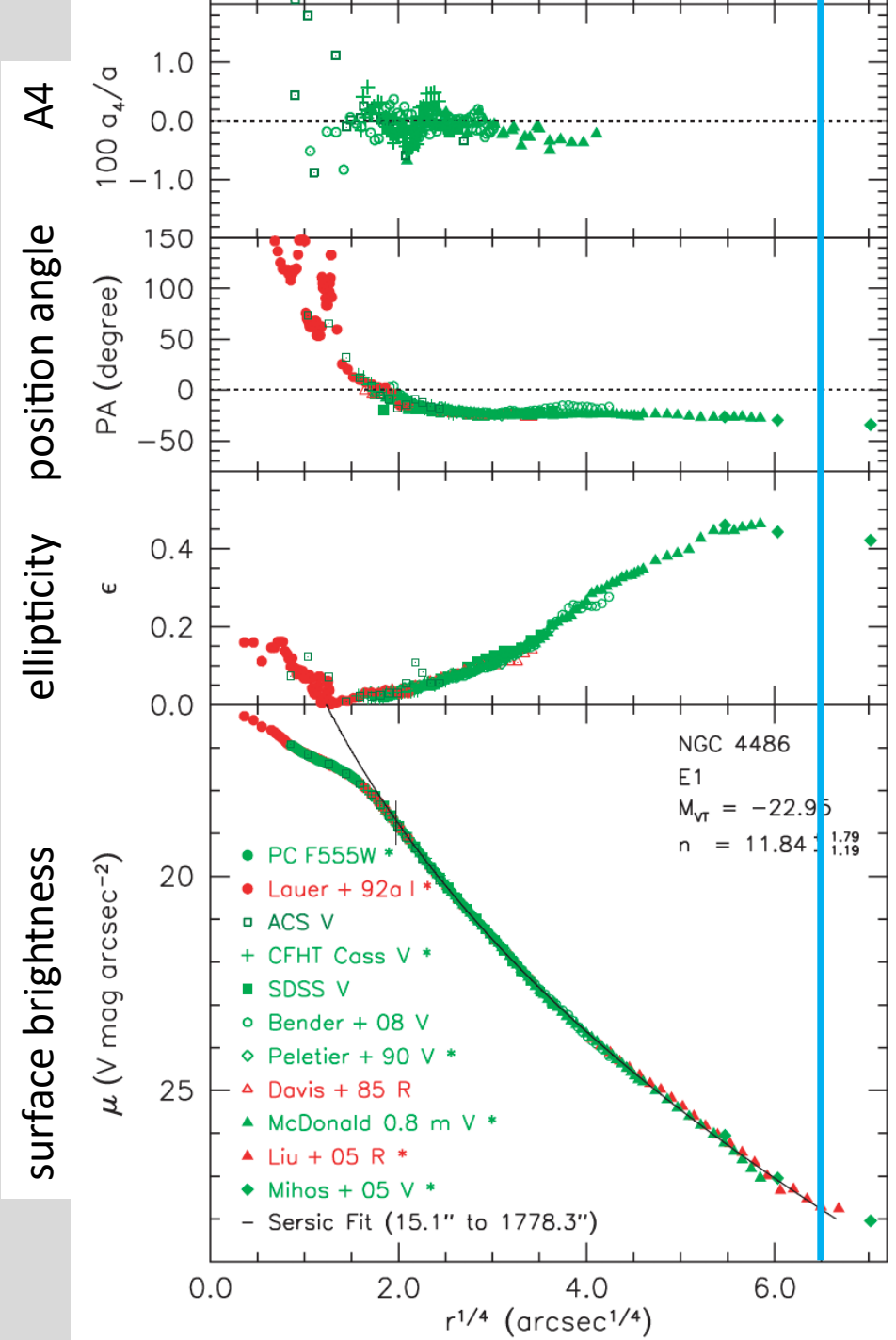


Isophotal Analysis: M87



CWRU Schmidt Image

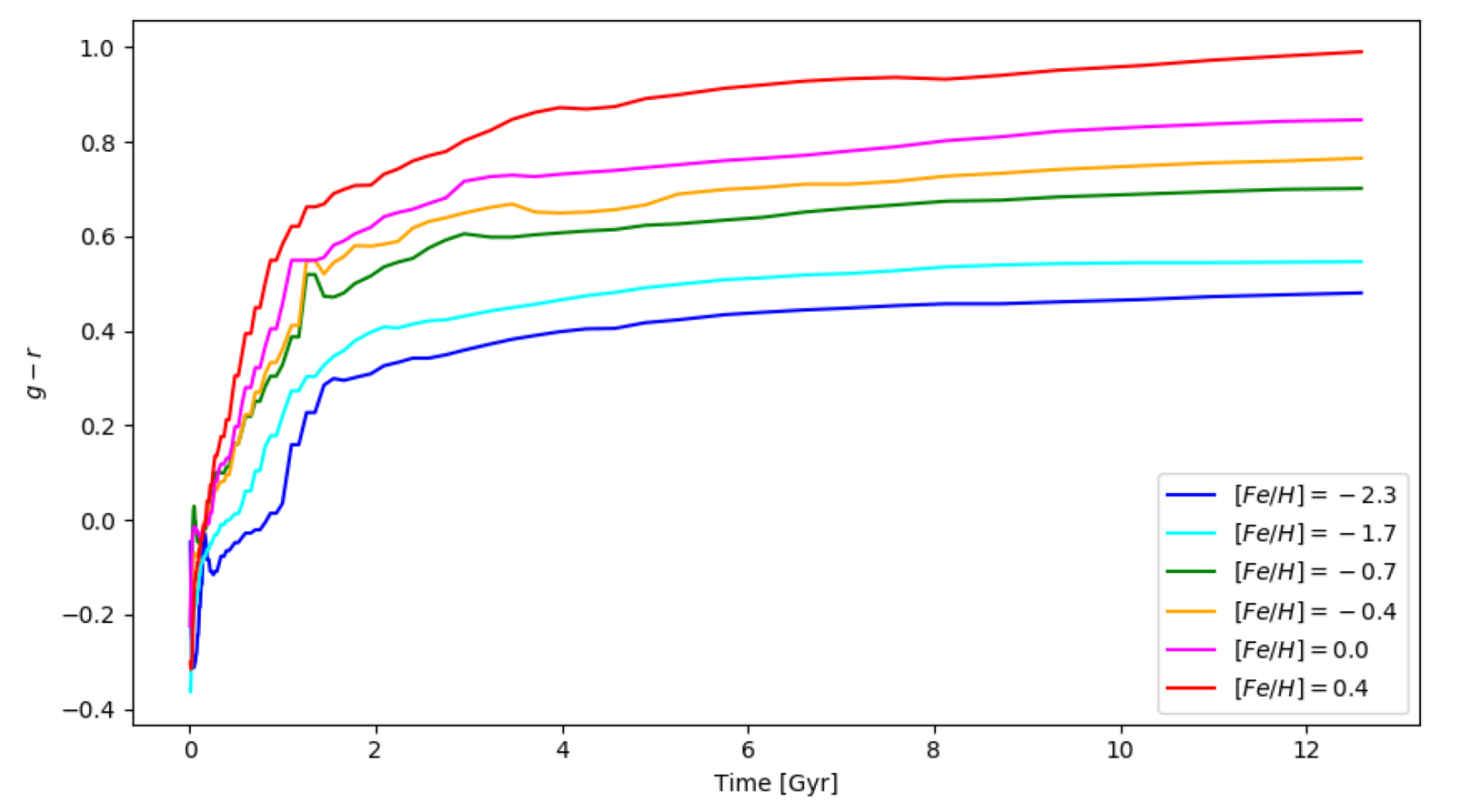




Elliptical Galaxies: Stellar Populations

Elliptical galaxies are typically ”red and dead”: old stellar populations with little or no ongoing star formation.

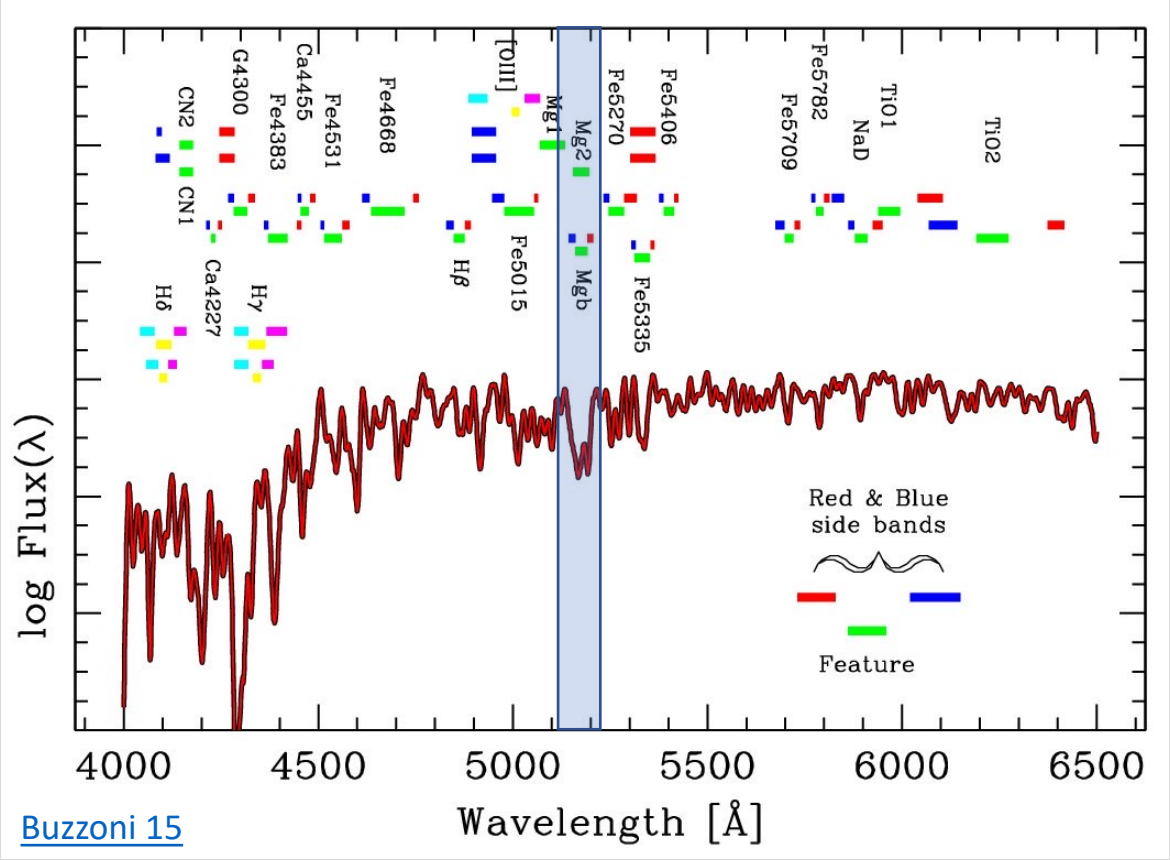
Remember: for old populations (> few Gyr), colors more indicative of metallicity than age:



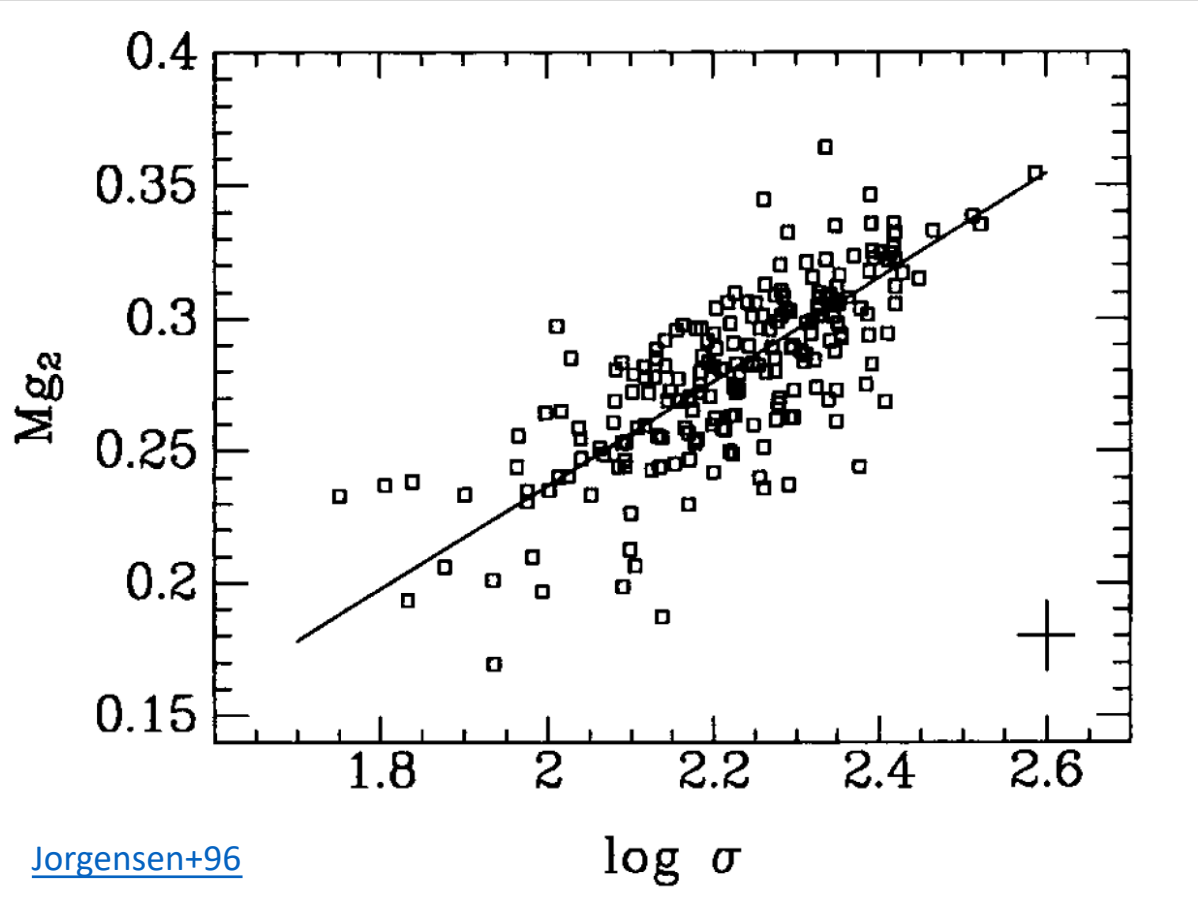
Mass-metallicity relationship

Mg2: strong absorption line in old stars (and therefore early type galaxies) which comes from magnesium ⇒ metallicity indicator

Mg2



Buzzoni 15



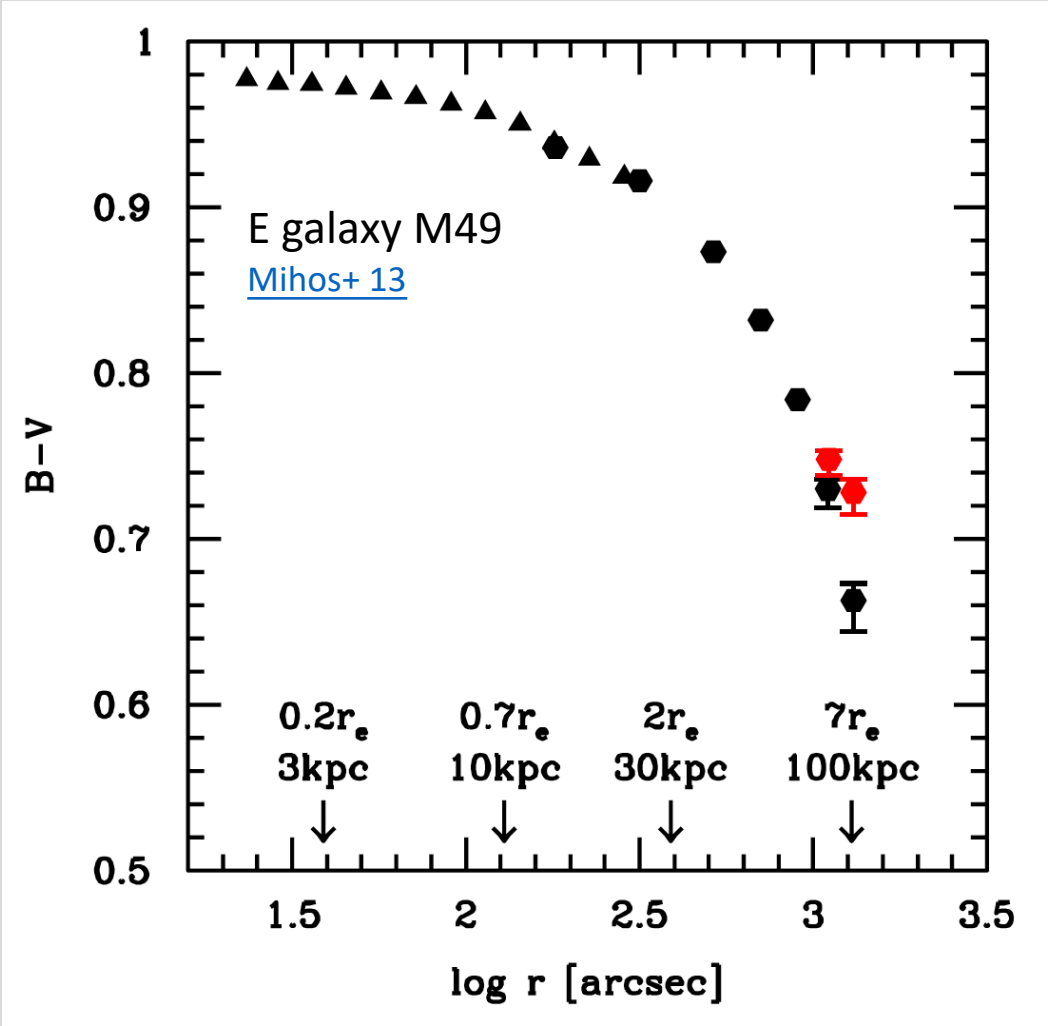
Jorgensen+96

⬆️ Strong correlation between metallicity (Mg_2) and velocity dispersion (σ) in E/S0 galaxies ⇒ **mass-metallicity relation**

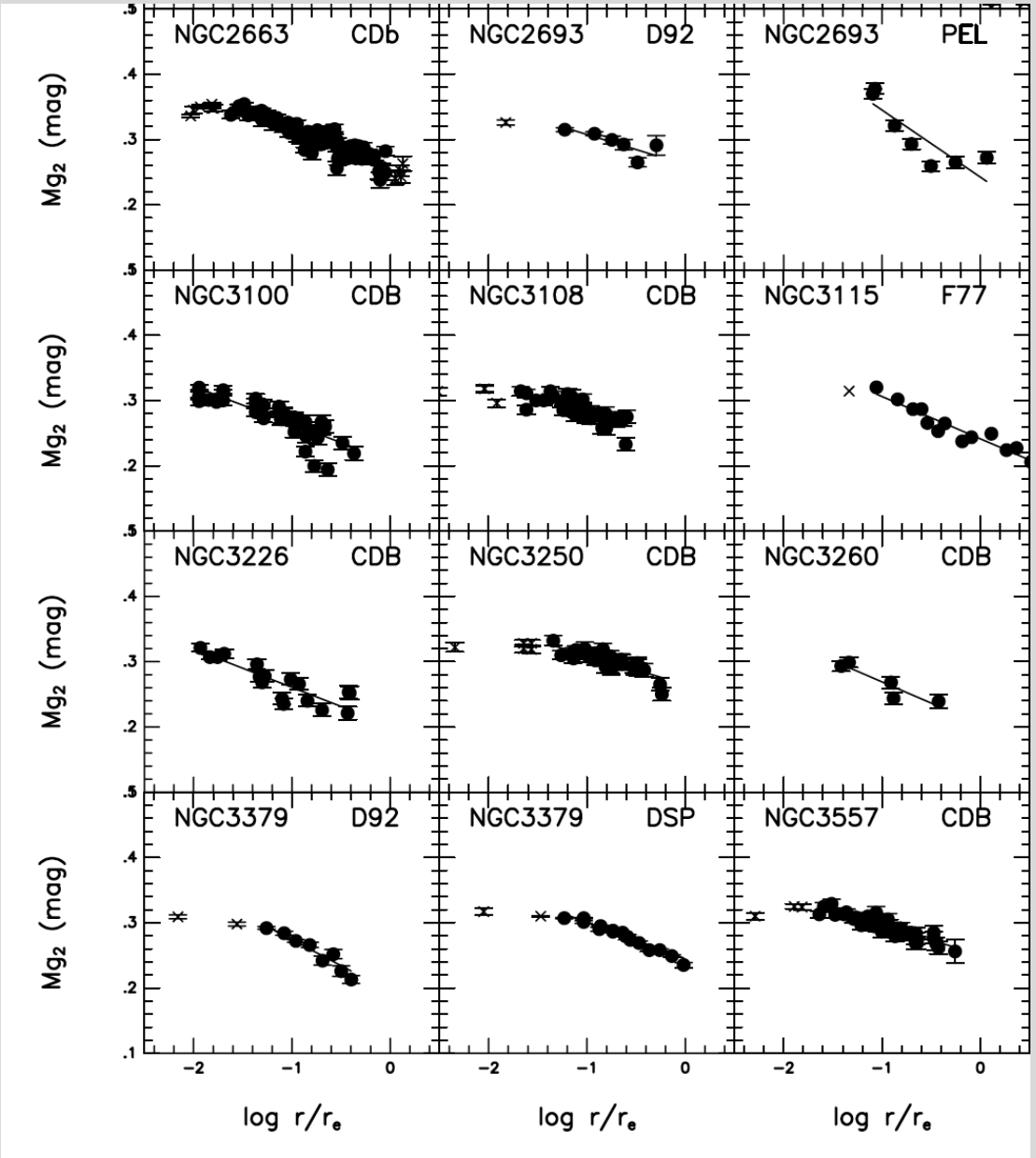
Main reason for the "tilt" (correlation between color and luminosity) in the red sequence.

Elliptical Galaxies: Stellar Populations

Elliptical galaxies show color gradients: redder interiors, bluer outskirts.



Spectroscopy confirms this is a metallicity effect.
(Mg_2 = magnesium line strength; Kobayishi & Arimoto 99)

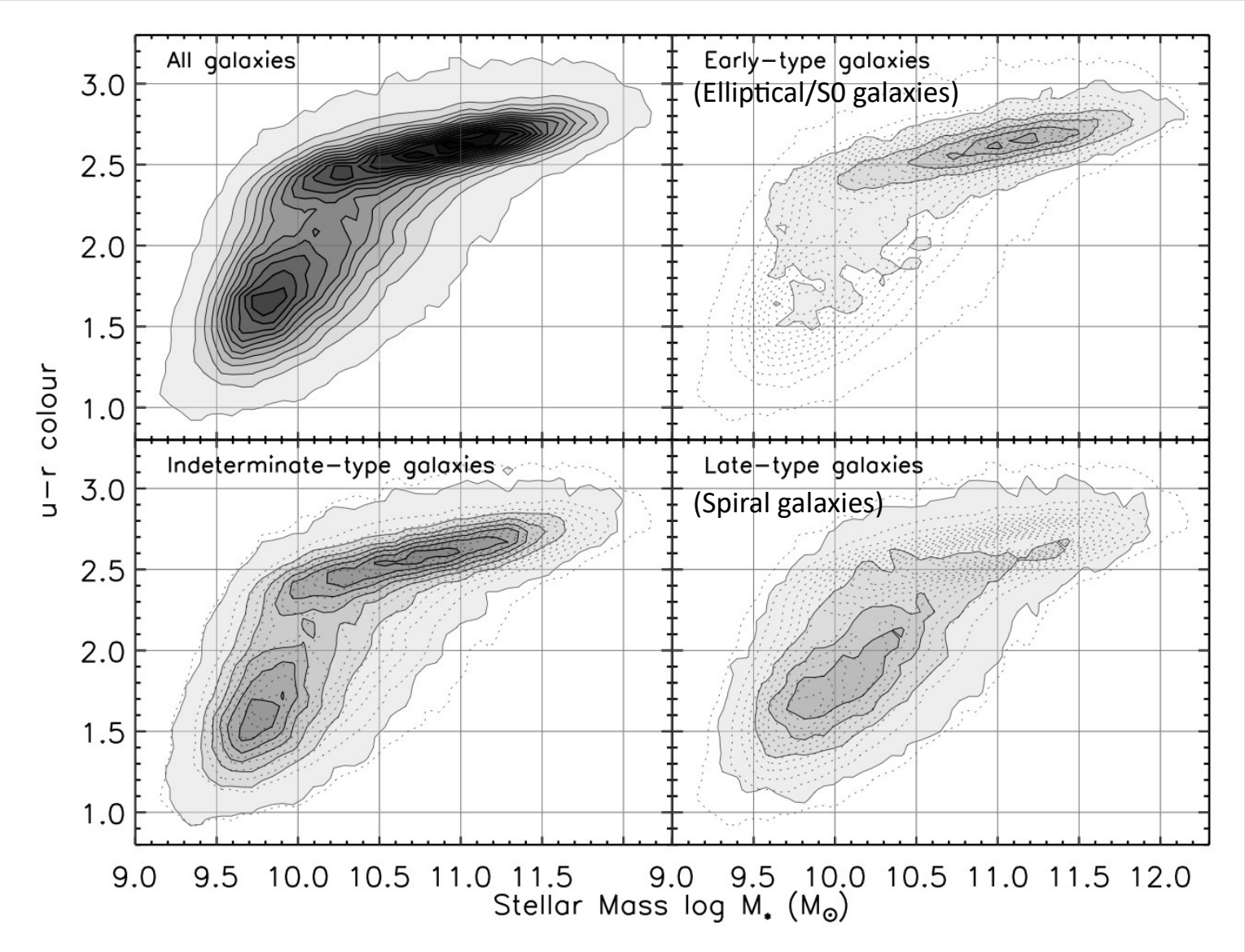


Elliptical Galaxies: Stellar Populations

courtesy K Schawinski

Similar effects give rise to the red sequence: massive ellipticals are redder because they are more metal-rich.

Note that when selected morphologically, there is a small population of ellipticals ("early-type galaxies") that fall in the blue cloud.



Elliptical Galaxies: Stellar Populations

Mass-Metallicity Relationship*: why?

One possibility: Feedback from star formation.

The combination of supernovae and stellar winds from massive stars adds lots of metals and energy to the surrounding gas in a galaxy.

More massive galaxies have deeper gravitational potential wells, so the gas cannot escape. New stars can form with higher metallicity. And so on....

Low mass galaxies have weak potential wells. The gas can escape and is lost. Since it is preferentially metal-rich, those metals are lost and any subsequent generation of stars will not be as metal-rich.

Mass-metallicity relationship holds for **all galaxy types…*

Starburst wind in M82

Elliptical Galaxies: Stellar Populations

Evidence for "*downsizing*":

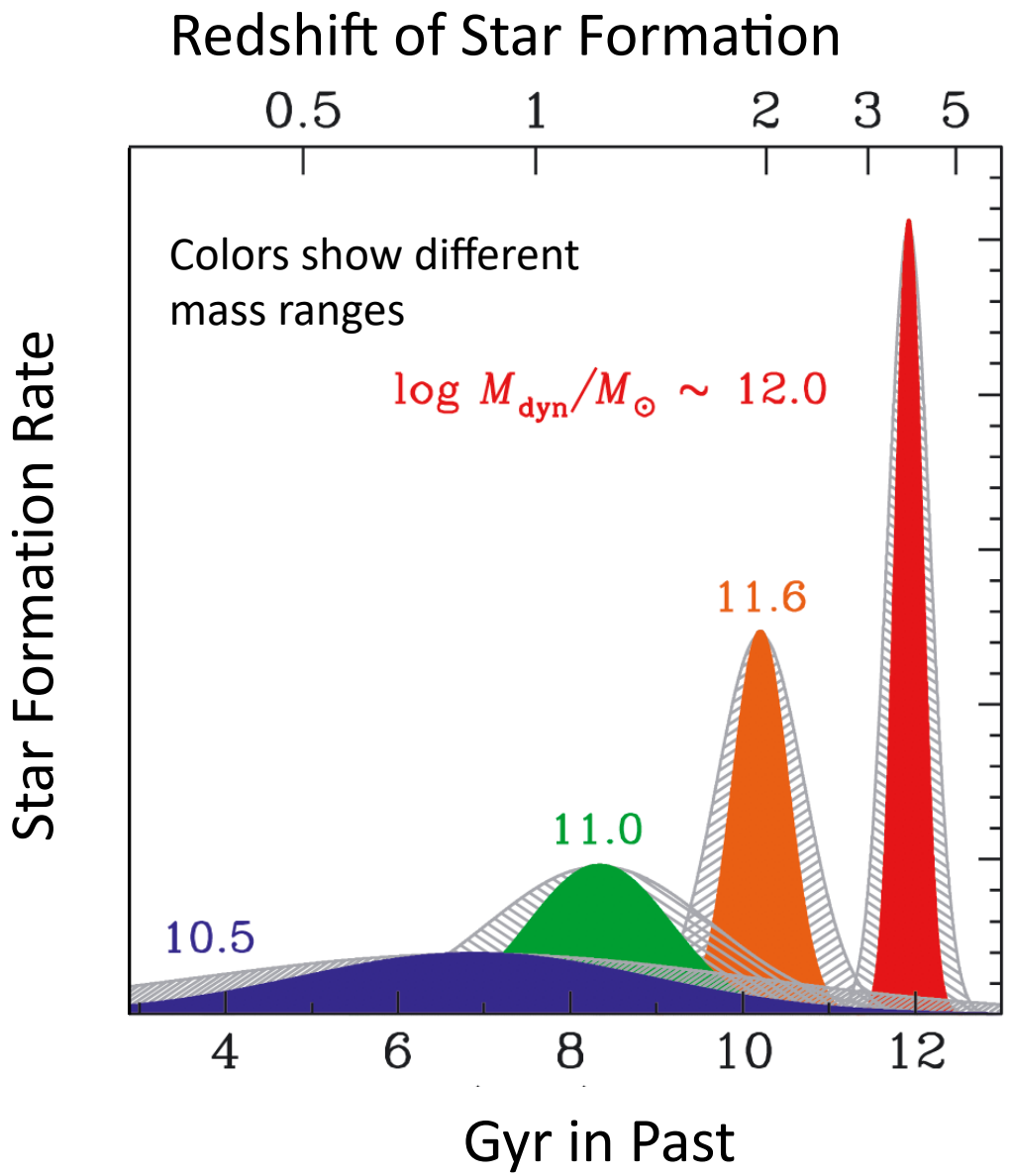
Stellar population modeling of ***nearby*** early-type galaxies in using SDSS spectroscopy.

Massive ellipticals contain stars that formed very early, less massive ellipticals show *slightly* younger populations.

Important Caveats:

- **This is not the cause of the red sequence tilt**: age differences too small to produce that much of a color change. Red sequence tilt ⇒ metallicity.
- **Age of stars is not the same as age of galaxy**. Heiarchical galaxy formation means stars can form in smaller galaxies but not merge together to form massive galaxy until later.

Thomas+ 10



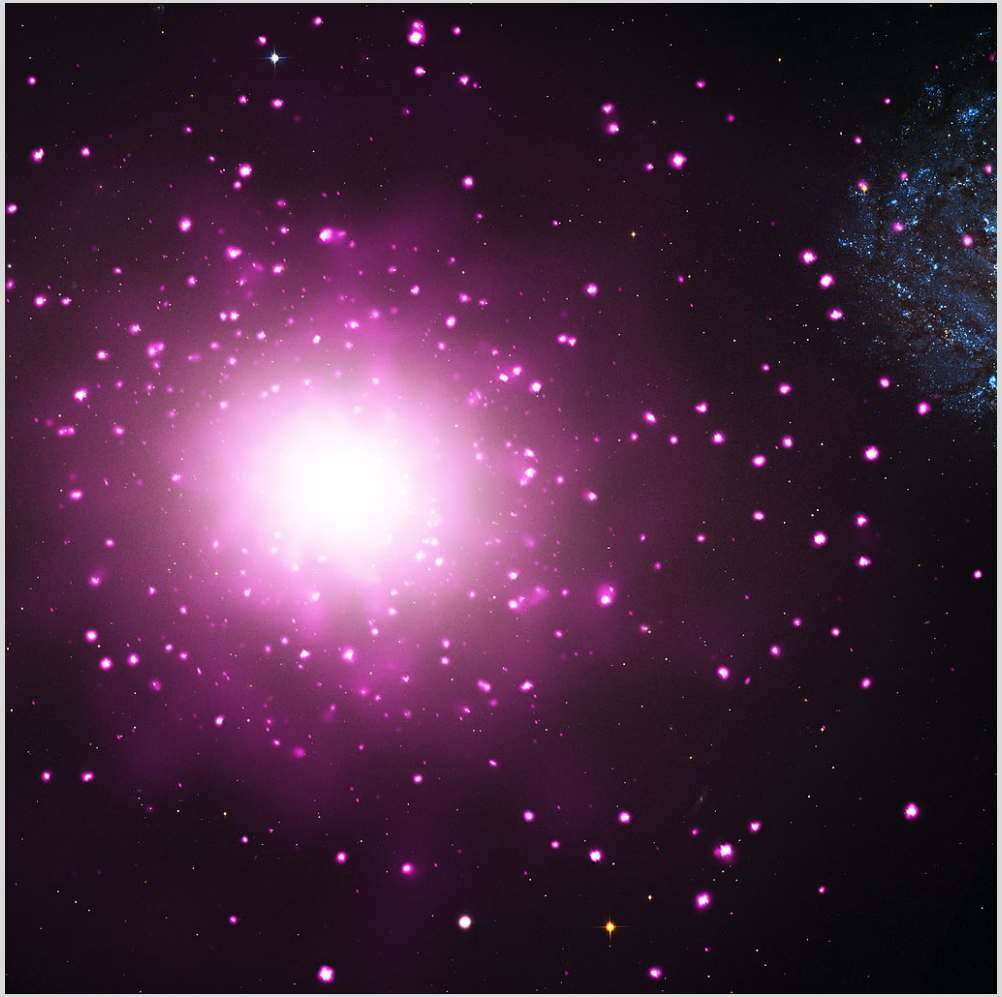
Elliptical Galaxies: Gas Content

Very little cold HI or molecular gas in elliptical galaxies.
Gas is hotter (10^7 K) and emitting X-rays.

Optical Starlight

NGC 4649
Strader+

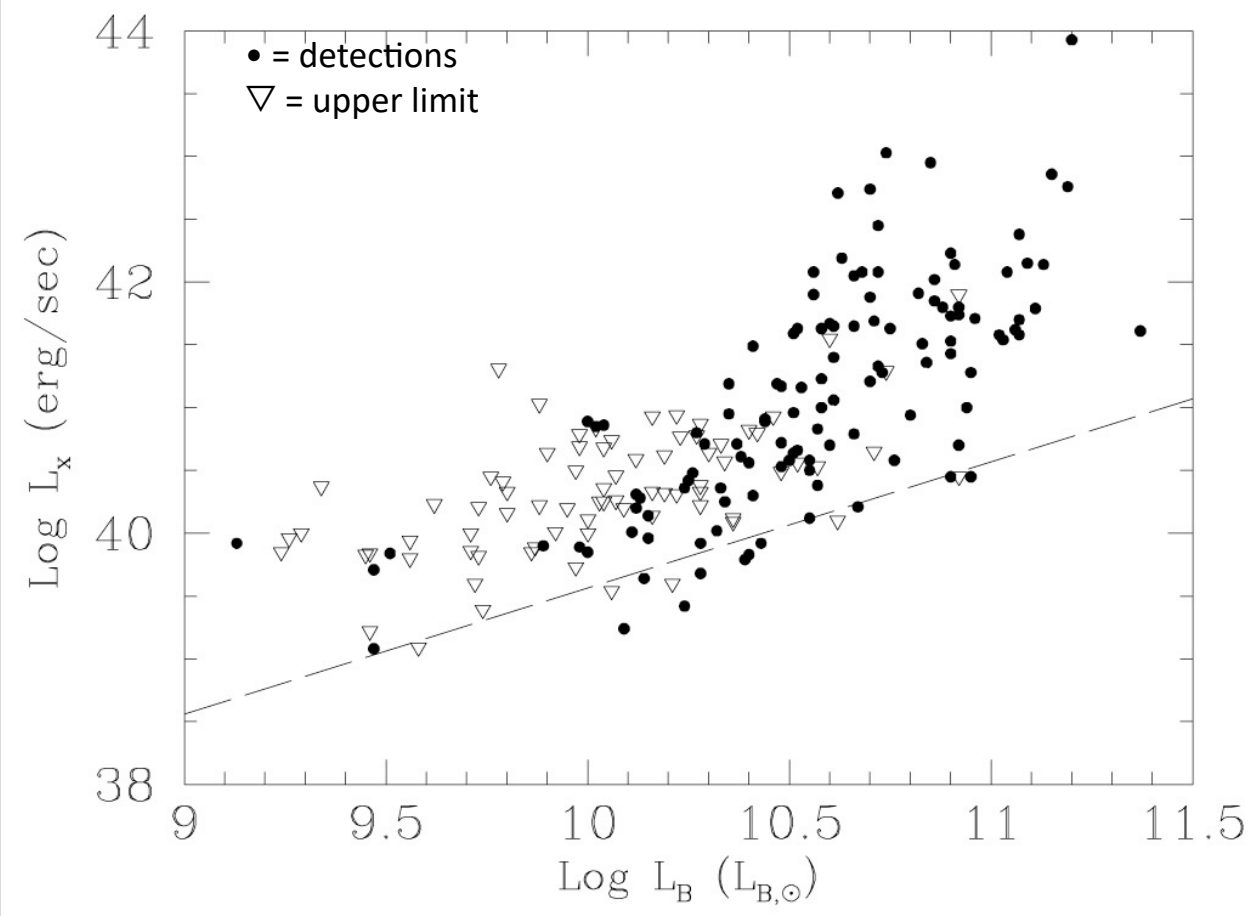
X-ray emission
diffuse emission: hot gas
point sources: accreting binary stars



Elliptical Galaxies: Gas Content

X-ray emission is significant in luminous ellipticals, inferred gas masses are $M_{gas} \approx 10^9 - 10^{11}\ M_\odot$ ($\approx 2\%$ of M_{stars})

X-ray luminosity vs optical luminosity
dashed line is expected X-ray emission for stars only
(Matthews & Brighenti ARAA 03)



Hydrostatic equilbrium: thermal pressure is in balance with gravitational potential energy:

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

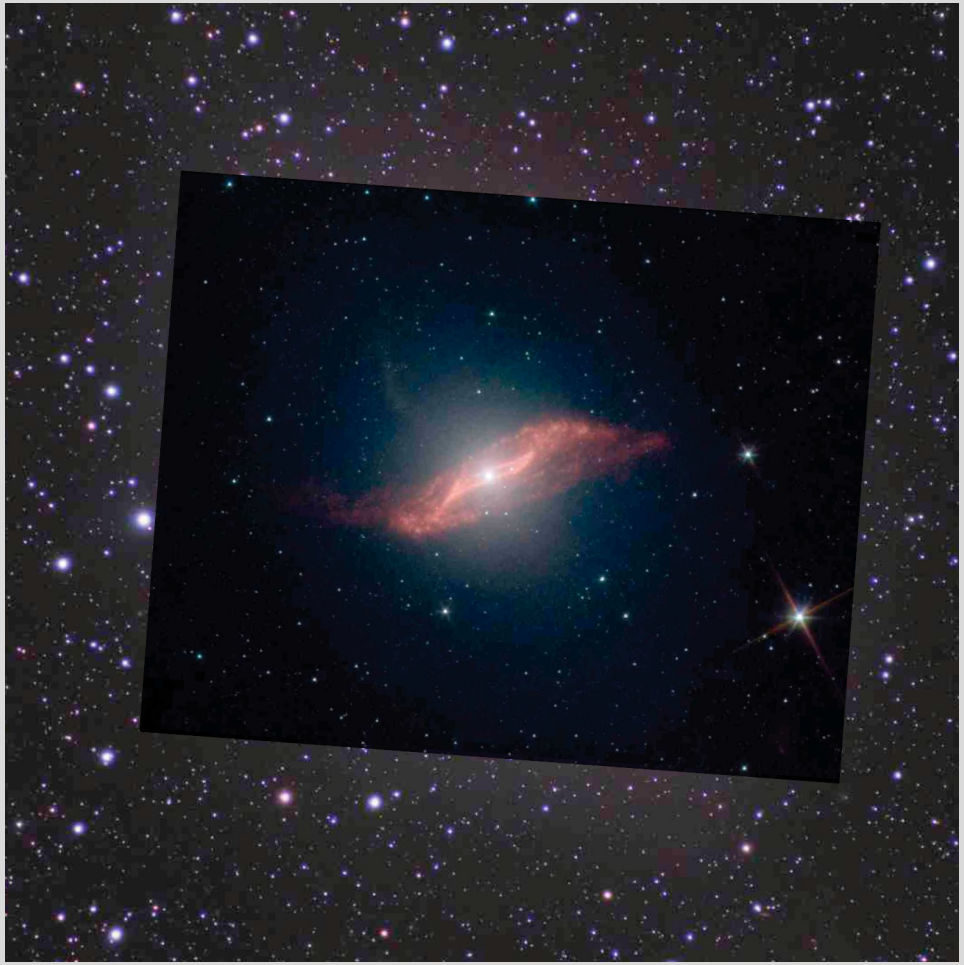
Using ideal gas law $P = \frac{\rho kT}{\mu m_p}$, we can solve for the total mass distribution:

$$M(r) = -rT(r)\frac{k}{G\mu m_p}\left(\frac{d\log\rho}{d\log r} + \frac{d\log T}{d\log r}\right)$$

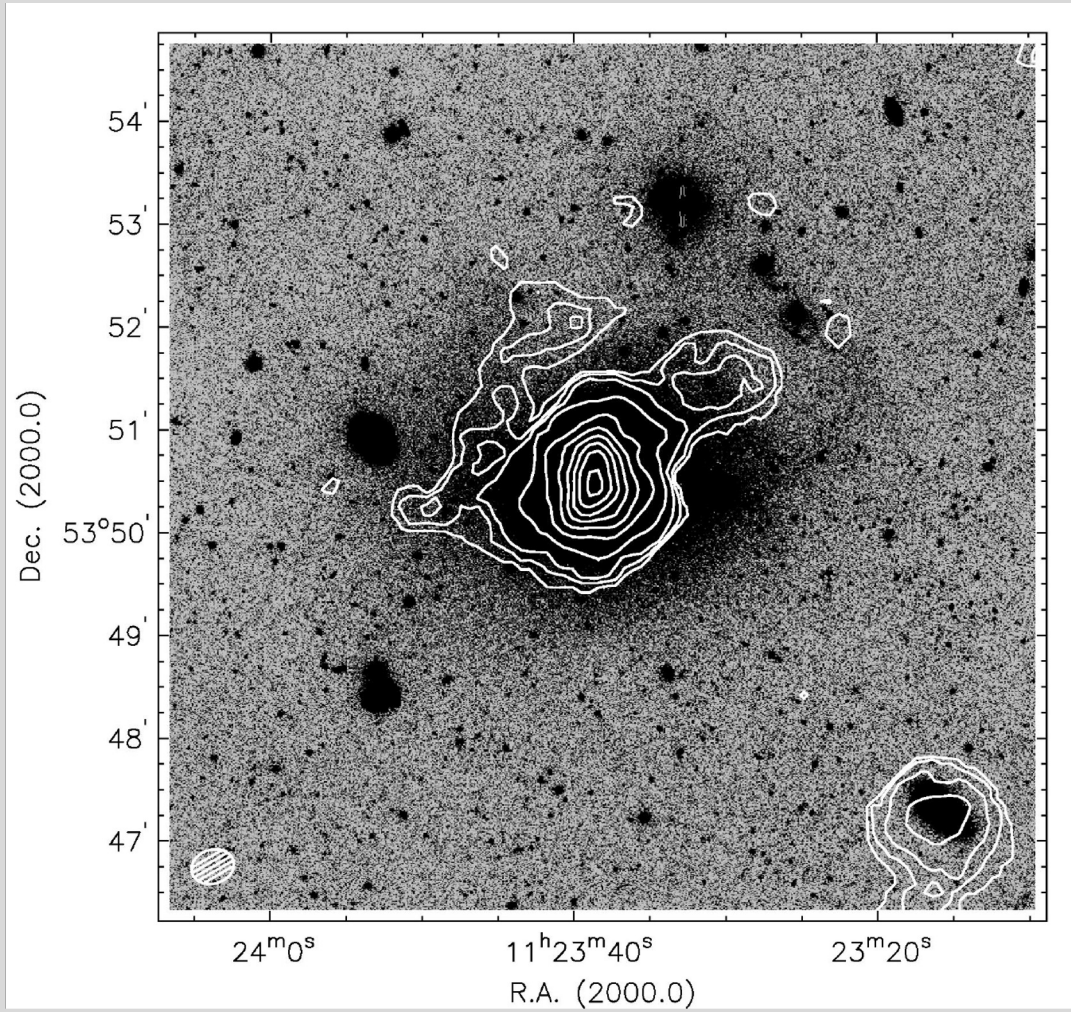
Given X-ray measures of gas density and temperature, we solve this to infer **elliptical galaxies also have massive dark matter halos**.

Elliptical Galaxies: Cold Gas

Not all elliptical galaxies are devoid of cold gas; some examples do exist. Often in morphologically peculiar ellipticals.



Centaurus A (courtesy T Oosterloo)



NGC 3656 (Balcells+ 01)

Elliptical Galaxies: Kinematics

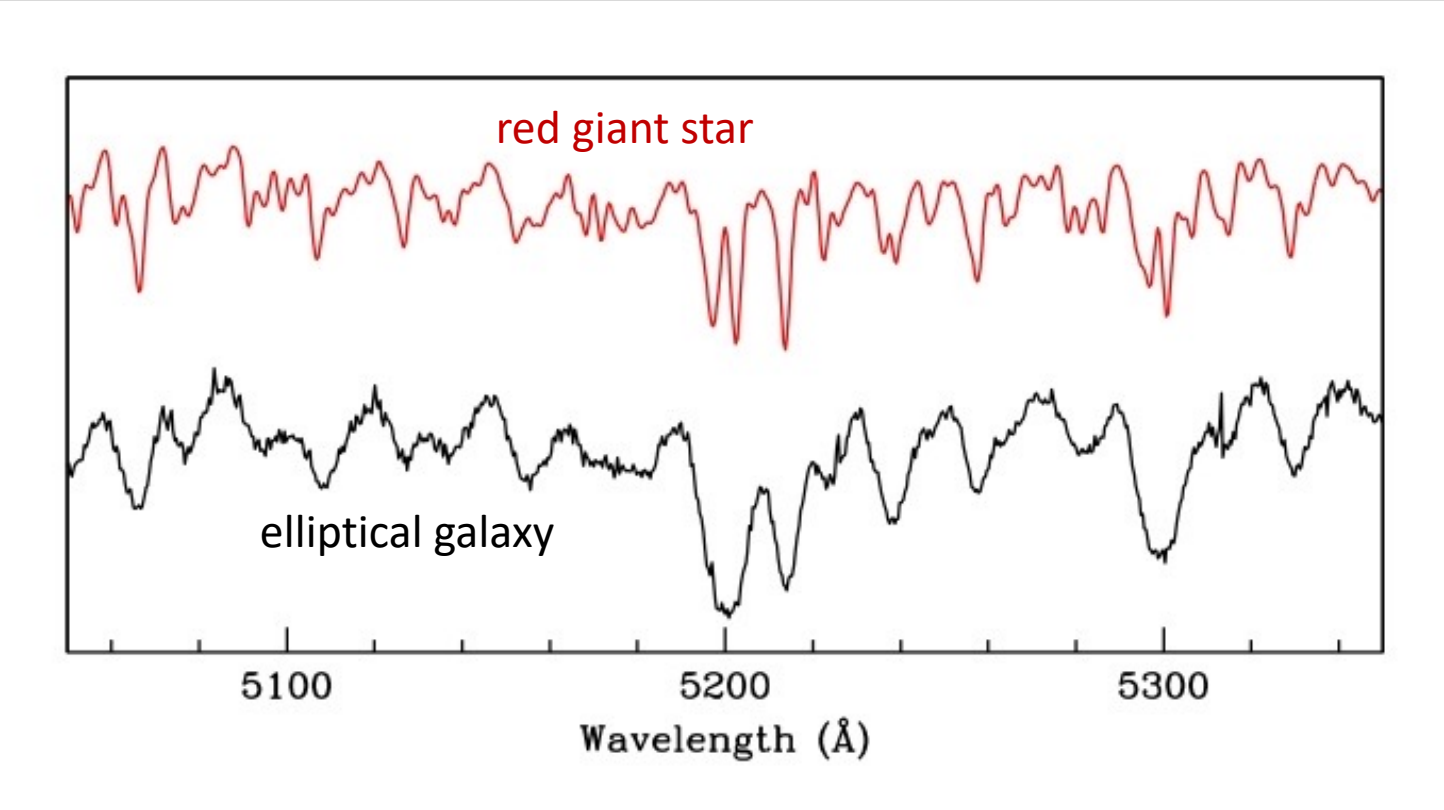
Without much cold gas or star formation, can't get kinematics from 21-cm or Hα emission lines. Must get kinematic information from stellar absorption lines, which is harder.

When we take a spectrum of an elliptical, we see projected stellar velocities, integrated along the line of sight. This broadens spectral lines.

Integrated light in ellipticals is dominated by old stellar populations: luminous red giants.

Take a red giant spectrum and broaden/shift it in wavelength to match observed galaxy spectrum.

Central wavelength and width of line gives us the mean line-of-sight velocity $\langle V \rangle$ and velocity dispersion (σ).



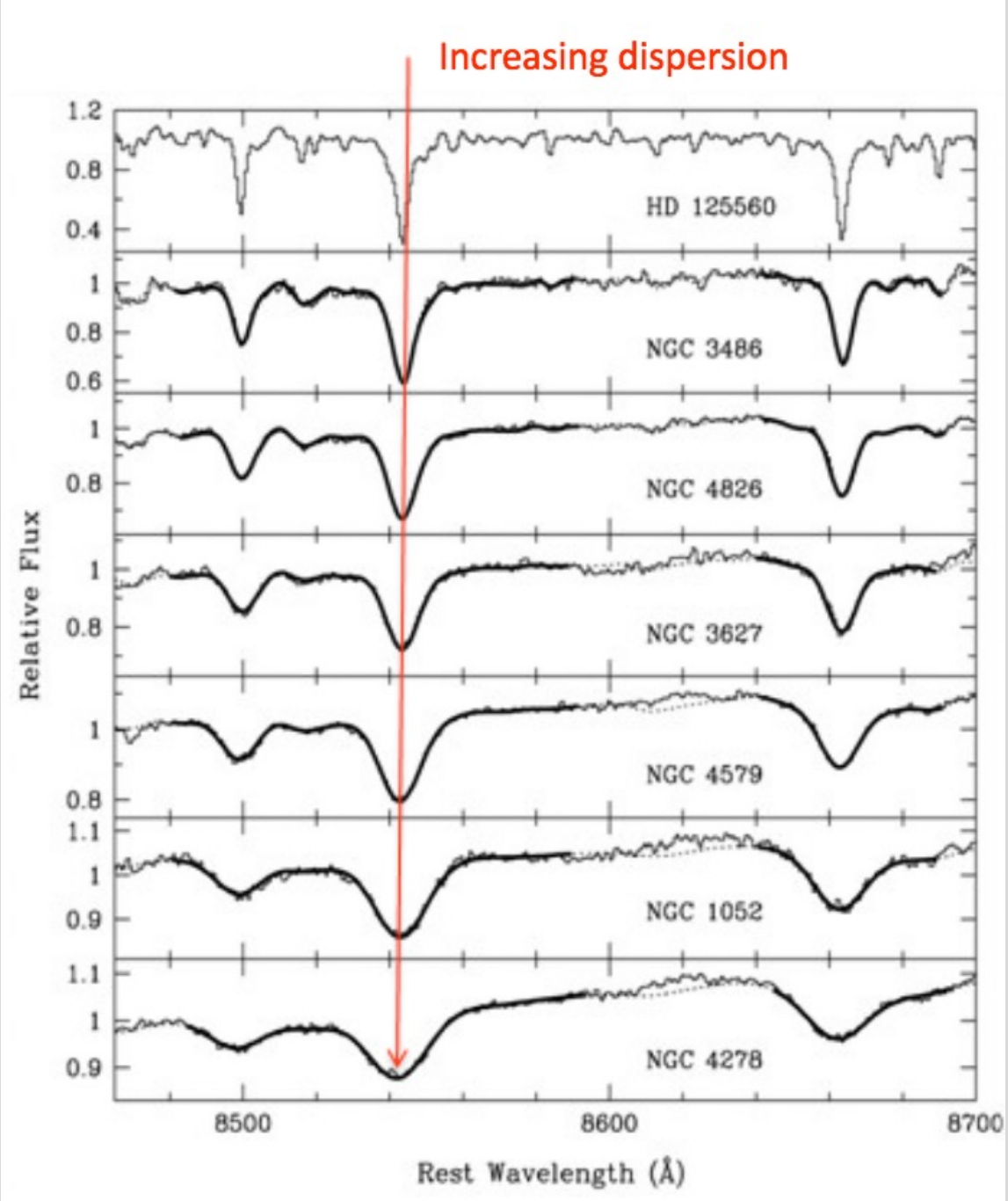
Broadening and velocity dispersion

Red giant star spectrum

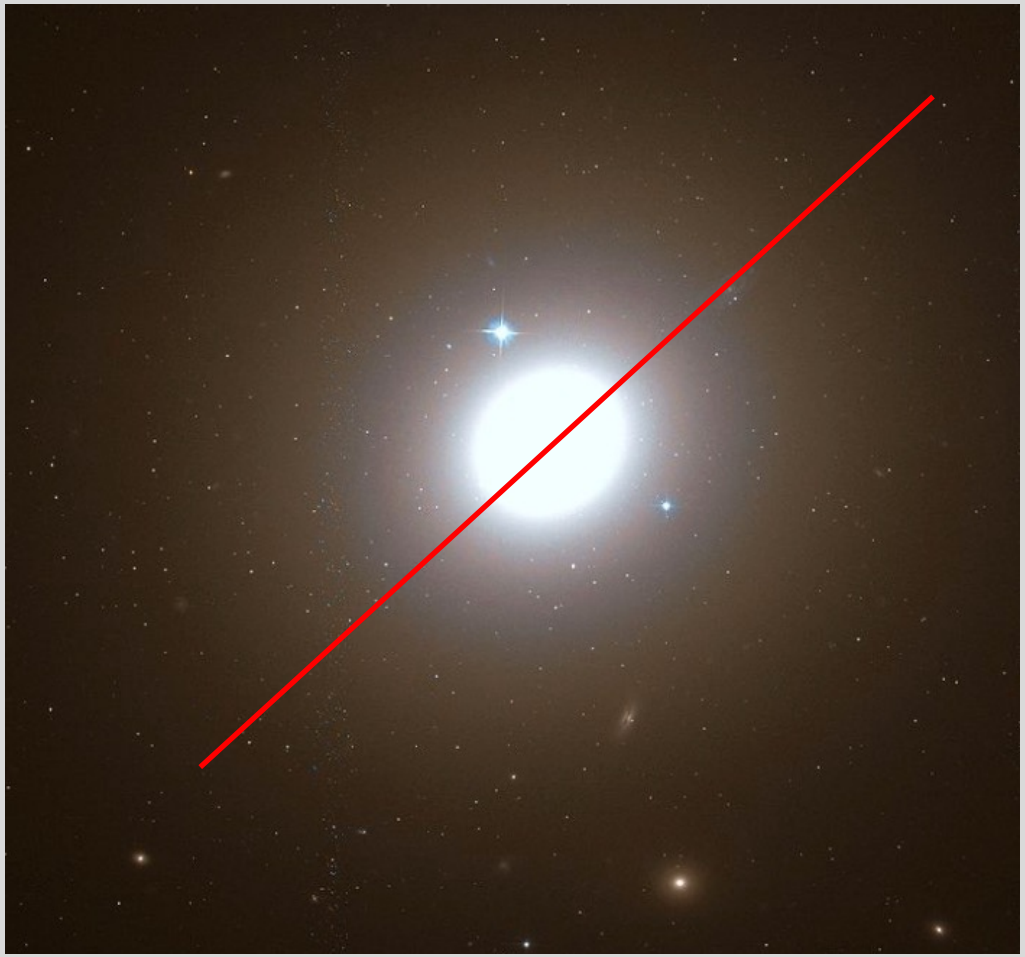
Absorption lines are broadened in wavelength, showing that ellipticals typically have low rotation (V_c) and large velocity dispersion (σ).

Elliptical galaxies are "kinematically hot" galaxies, with $V_c/\sigma < 1$.

Galaxies



Elliptical Galaxies: Major Axis Kinematics



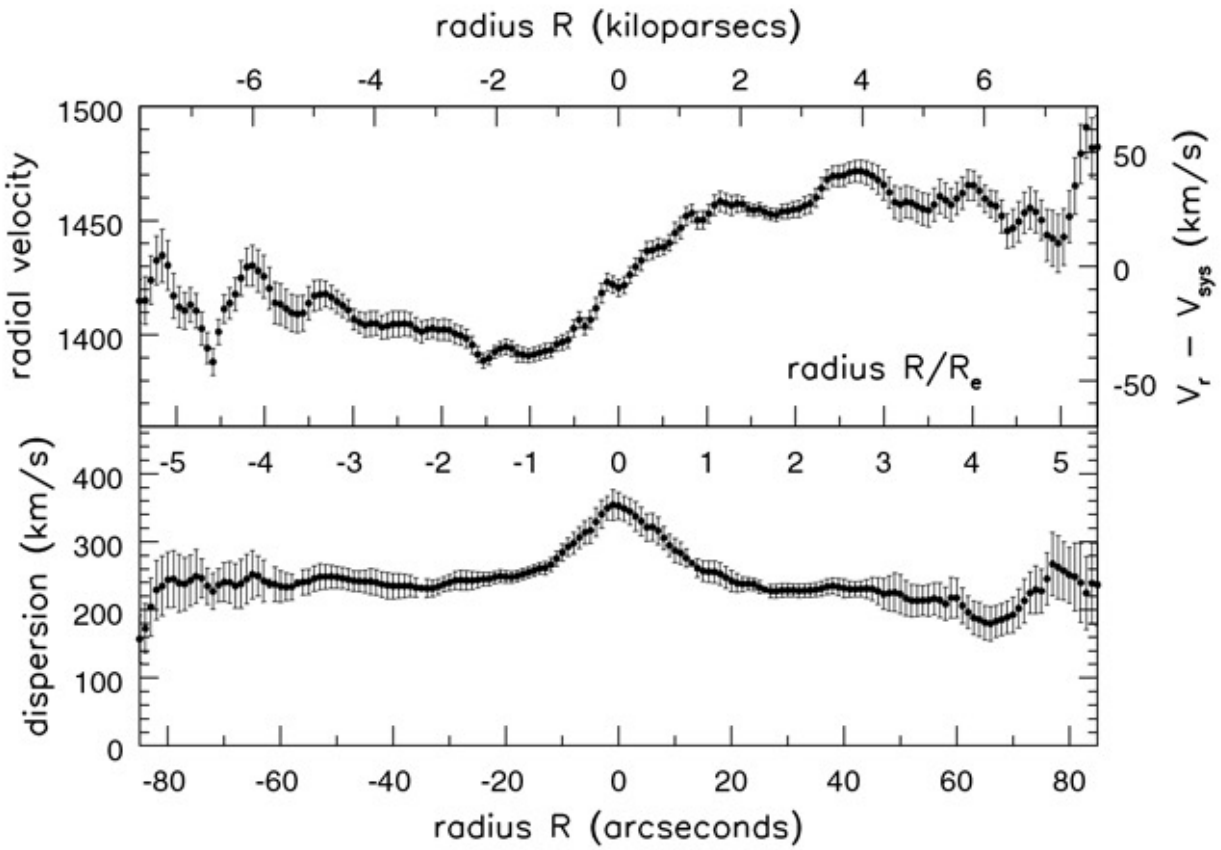


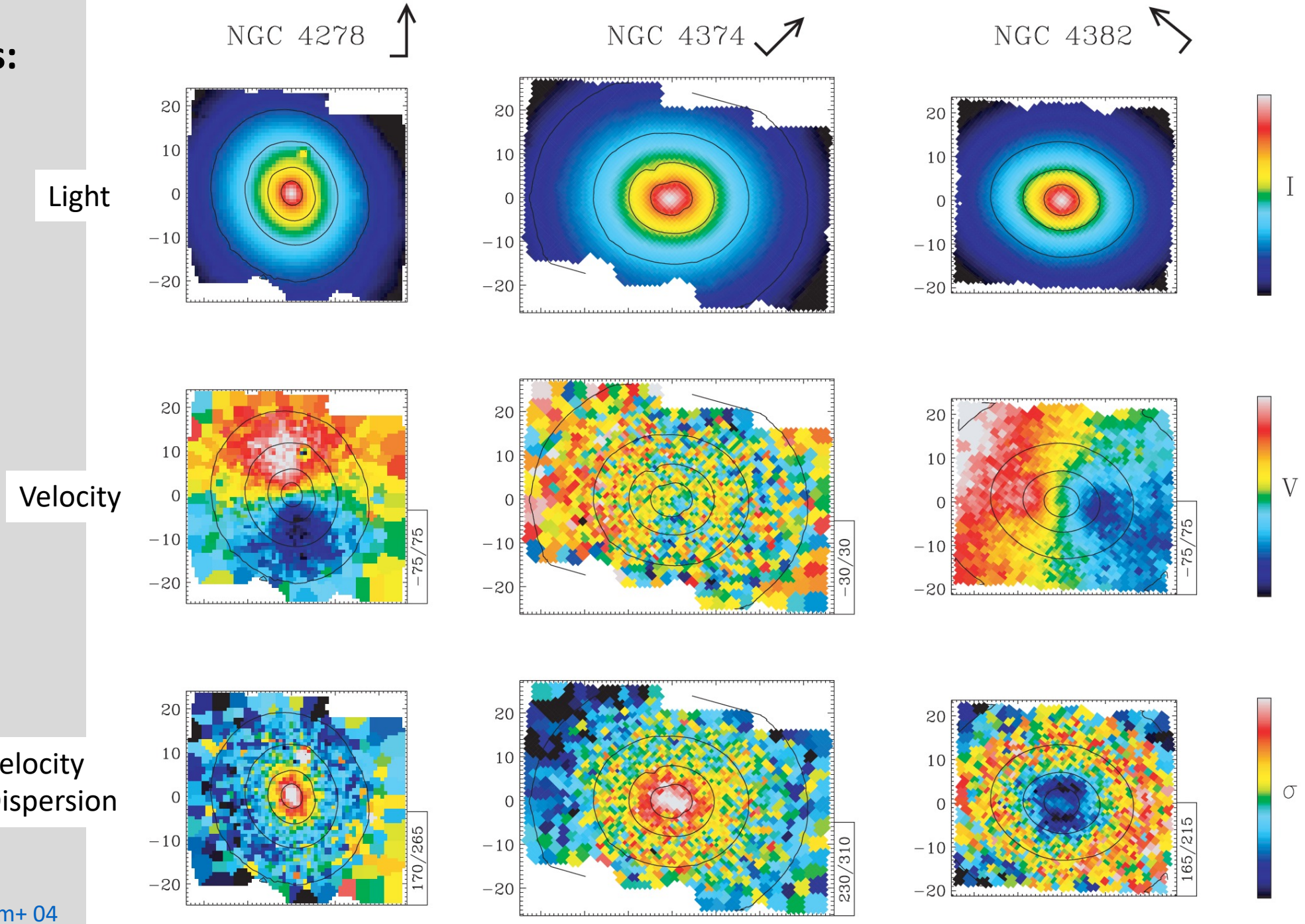
Fig 6.12 (A. Graham) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

NGC 1399: $\sigma \approx 350$ km/s, $V_c \approx 35$ km/s, $V_c/\sigma \approx 0.1$

(Compare to Milky Way disk: $\sigma \approx 30$ km/s, $V_c \approx 220$ km/s, $V_c/\sigma \approx 7.3$)

Elliptical Galaxies: 2D Kinematics

We can see a modest amount of rotation in many ellipticals.



Emsellem+ 04

Elliptical Galaxies: Projected vs True Velocity dispersion

We observe / measure a projected ***line of sight*** velocity dispersion: σ_{los}
But physically, the stars have motion in 3 directions, with a total dispersion given by: $\sigma_v^2 = \sigma_r^2 + \sigma_\theta^2 + \sigma_\varphi^2$

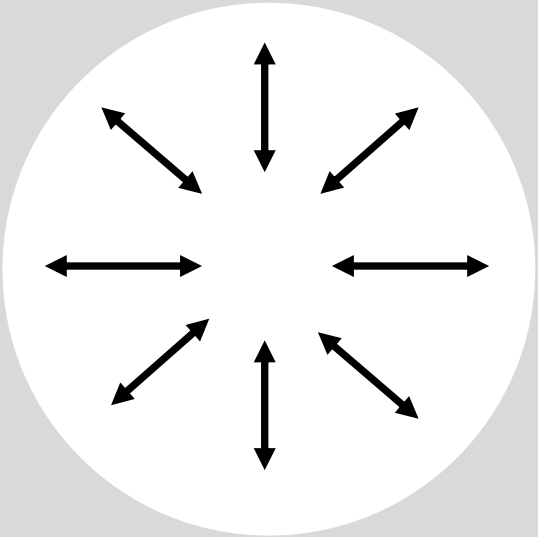
How do we relate these things?

- Assume **isotropy**:
  - $\sigma_r = \sigma_\theta = \sigma_\varphi$, then $\sigma_v = \sqrt{3}\sigma_{los}$

- Assume **radial anisotropy**:
  - $\sigma_r \neq \sigma_\theta = \sigma_\varphi$.
  - Anisotropy parameter: $\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\varphi^2}{2\sigma_r^2}$.
    - $\beta = 1$: radial orbits
    - $\beta = 0$: isotropic orbits
    - $\beta = -\infty$: circular orbits *(but not necessarily net rotation!)*

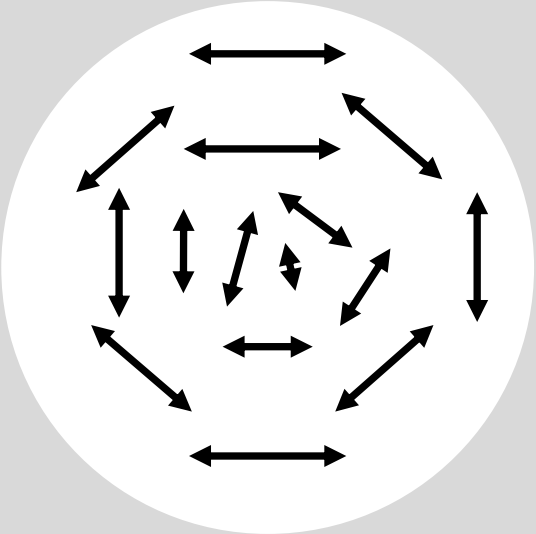
Thought experiment: what would the projected velocity dispersion profile $\sigma_{los}(R)$ look like for a galaxy with:
- Large radial anisotropy: $\beta \sim 1$
- Large tangential anisotropy: $\beta < -1$

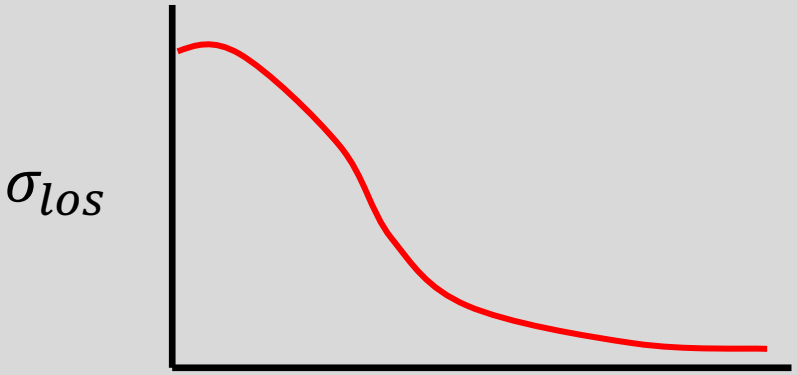
Radial Anisotropy ($\beta \approx 1$)

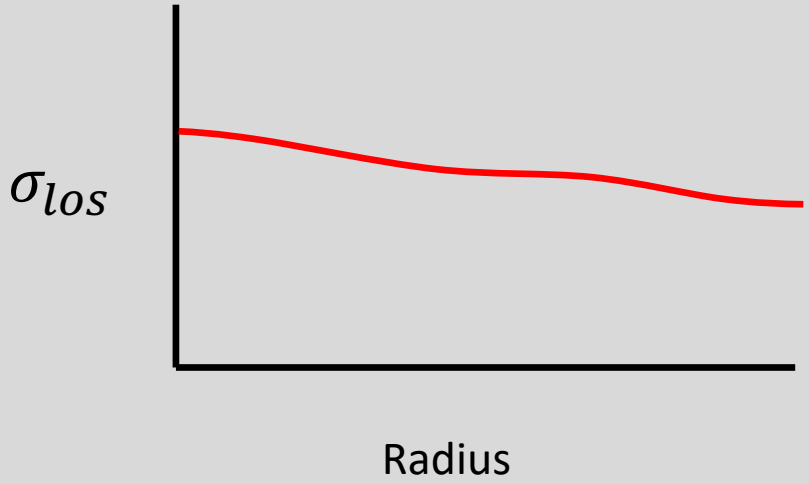


$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\varphi^2}{2\sigma_r^2}$$

Tangential Anisotropy ($\beta \ll -1$)







Example: Dark Matter vs Anisotropy

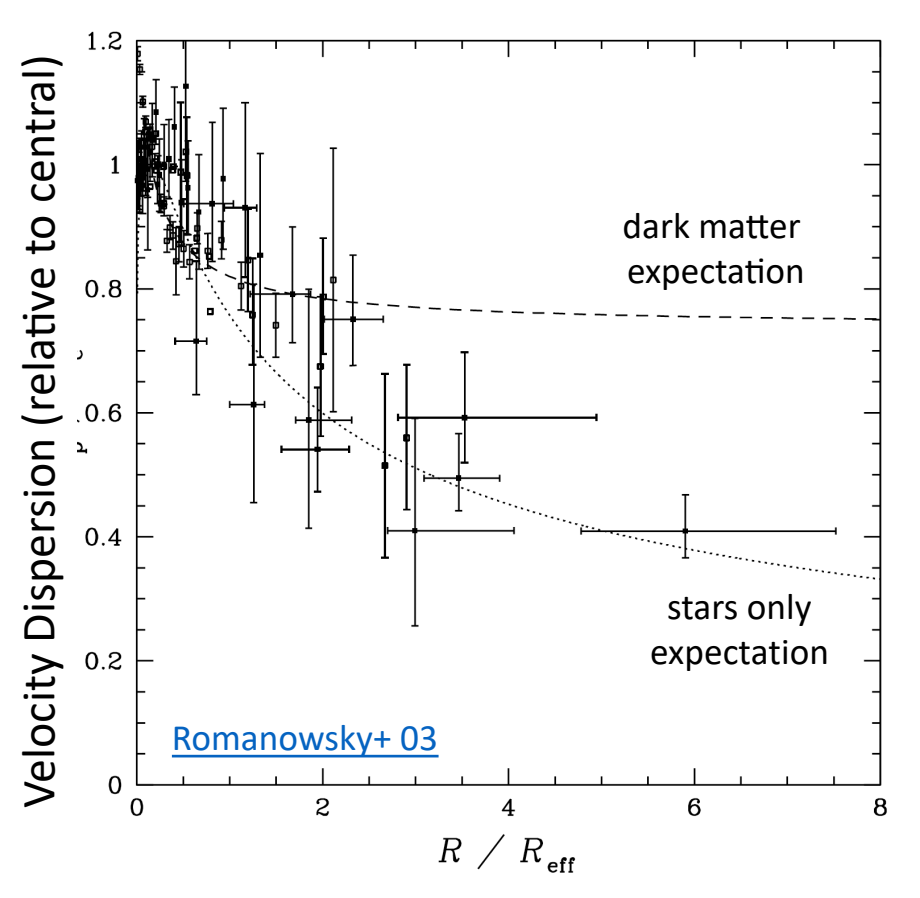
Projected velocity dispersion measures decline at large radius in some eliipticals.

For isotropic models, this would mean no dark matter:

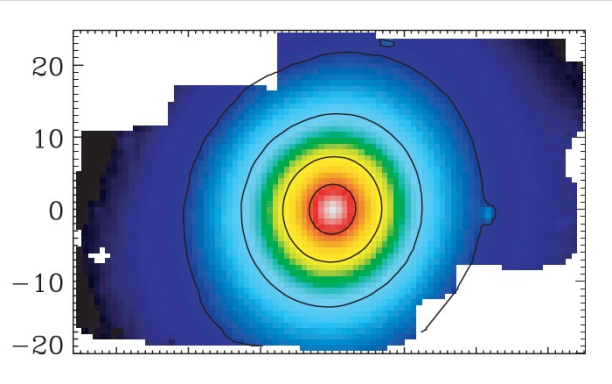
$$\sigma_v^2 = 3\sigma_{los}^2 \sim GM_{stars}(r)/r$$

But could also be due to large radial orbit anisotropy ($\beta > 0$) in outer regions, which would make the velocity dispersion drop faster with radius.

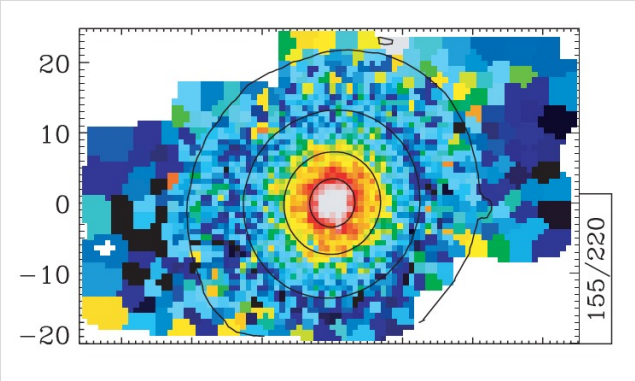
How can we tell? With exquisite data, radial orbits and tangential orbits give different line profile shapes and can be determined spectroscopically.



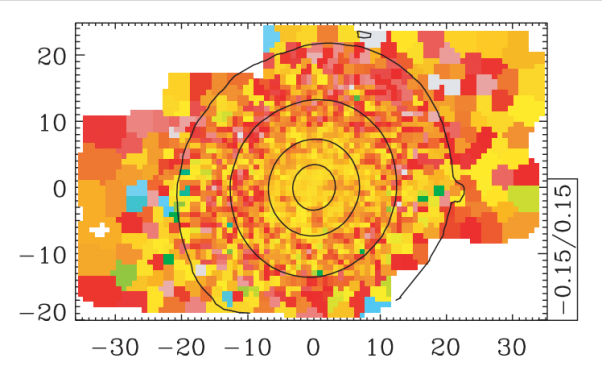
NGC 3379 Emsellem+ 04



Light profile



Velocity dispersion



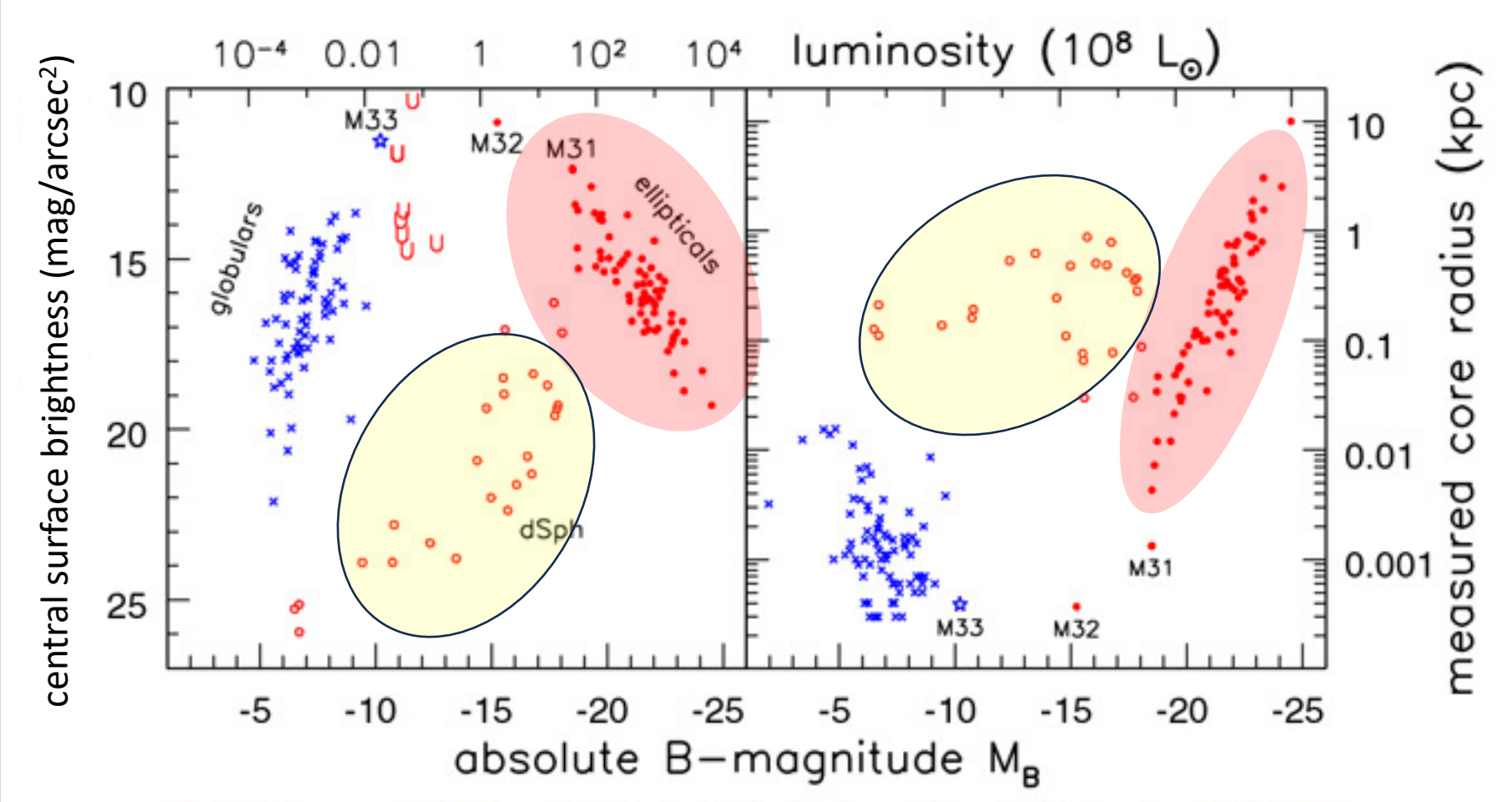
Radial anisotropy

yellow: isotropic
red: radially biased

Structural relations

For ellipticals, luminous galaxies are larger and lower in surface brightness (more diffuse).

Note that dwarf spheroidals behave differently – they are not just "scaled down" ellipticals.
So as we talk about ellipticals, we are talking about mid-to-large ellipticals, not dwarfs.



S&G Fig 6.6

Scaling relationships: kinematic

Simple correlations between structural and kinematic properties are weaker than in spirals.

Recall tight correlation between V_{rot} and L for spirals, the Tully-Fisher relationship.

For ellipticals, the analogous relationship is the Faber-Jackson relationship connecting luminosity (abs-mag) and velocity dispersion:

$$M = a \log \sigma + b.$$

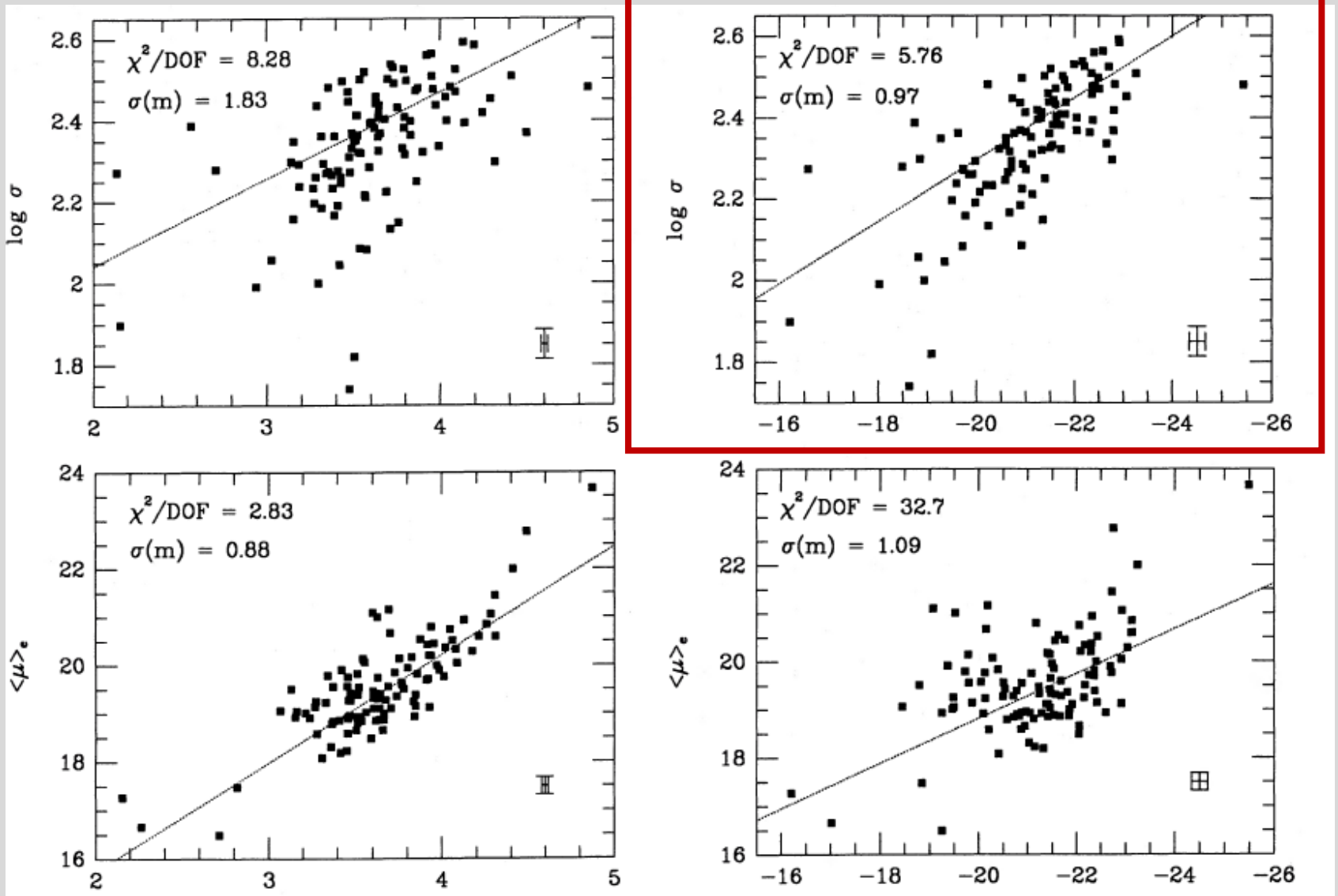
But F-J shows much more scatter than T-F!

σ: velocity dispersion
$\langle \mu \rangle_e$: average surface brightness
r_e: effective radius
M: total absolute magnitude

$h = H_0/100$

Djorgovski & Davis 87

Faber-Jackson relation



log r_e (h^{-1} pc)

Absolute Mag (for h=1)

Scaling relationships: The Fundamental Plane

But tight correlation between a combination of parameters: size (r_e), velocity dispersion (σ), and surface brightness (μ_e or I_e).

σ: velocity dispersion
$\langle I \rangle_e$: average surface brightness (in flux units, not mag/arcsec^2)
r_e: effective radius

The Fundamental Plane:

$$r_e \sim \sigma^x I_e^y$$

or

$$\log r_e = x \log \sigma + y \log I_e$$

$$x \approx 1.24, y \approx -0.82$$

(in Gunn r filter)

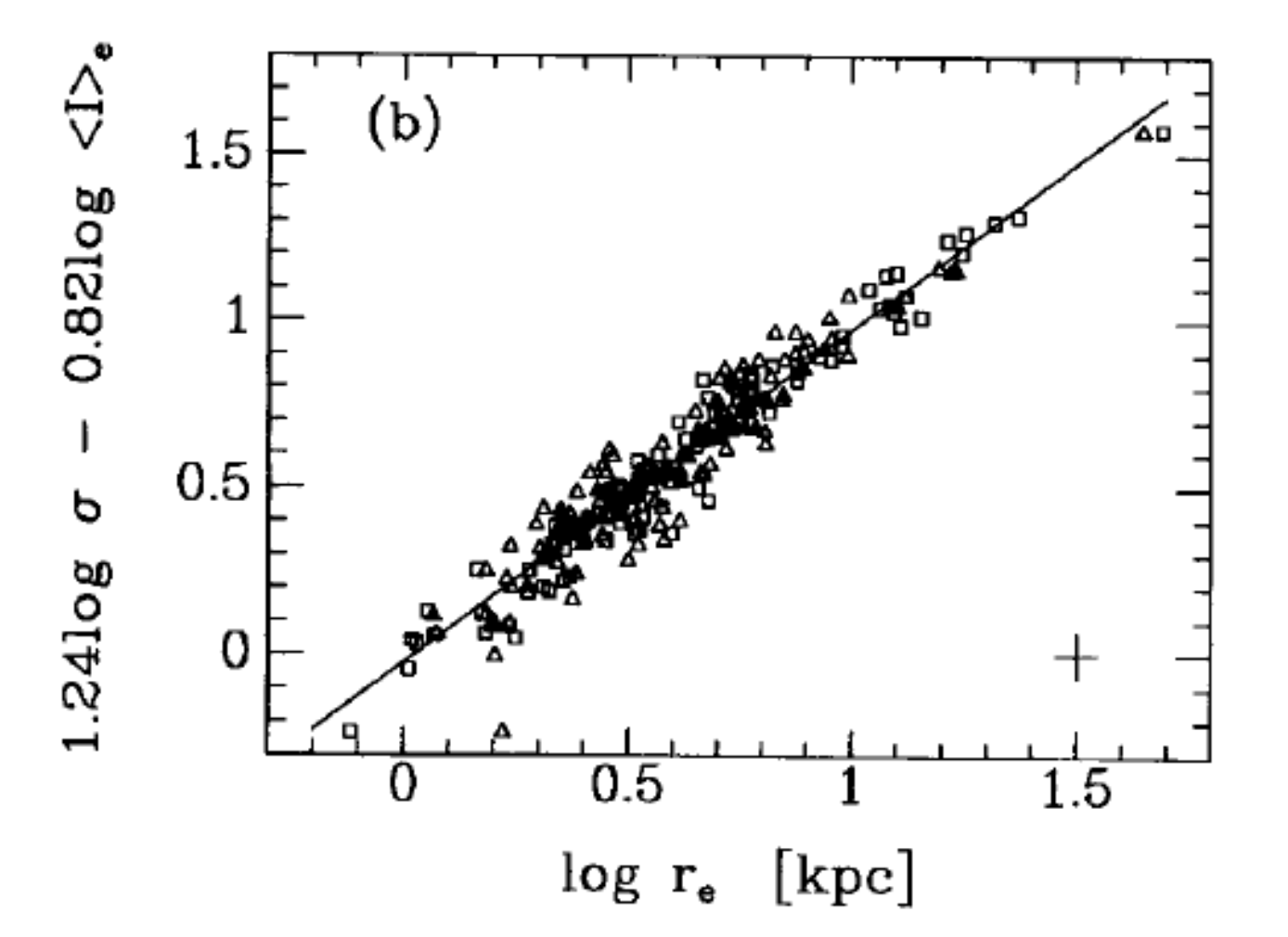
Simple gravitational scaling arguments would predict (recall the discussion of Tully-Fisher):

$$r_e \sim \sigma^2 I_e^{-1} \left(\frac{M}{L}\right)^{-1}$$

Why the difference with the observed parameters?

- changes in (M/L)?
- velocity anisotropy?

Jorgensen+96



The Importance of Scaling relationships

A means to **derive distances** to galaxies:

Note that one axis always is distance-dependent (M_R or physical r_e), the other is distance-independent observable (W or σ and I). If you apply the scaling relationship, the observables give you the distance.

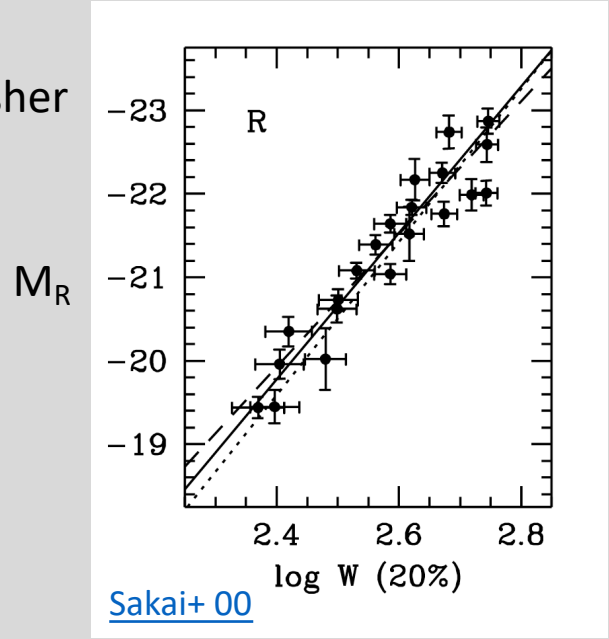
A means to **study galaxy evolution** and stellar populations:

One axis always involves light (M_R or I). If you know distance, you can compare observed light with expectation from the scaling relationship. Discrepancies tell you about intrinsic variations between galaxies.

A means to **study dark matter** in galaxies:

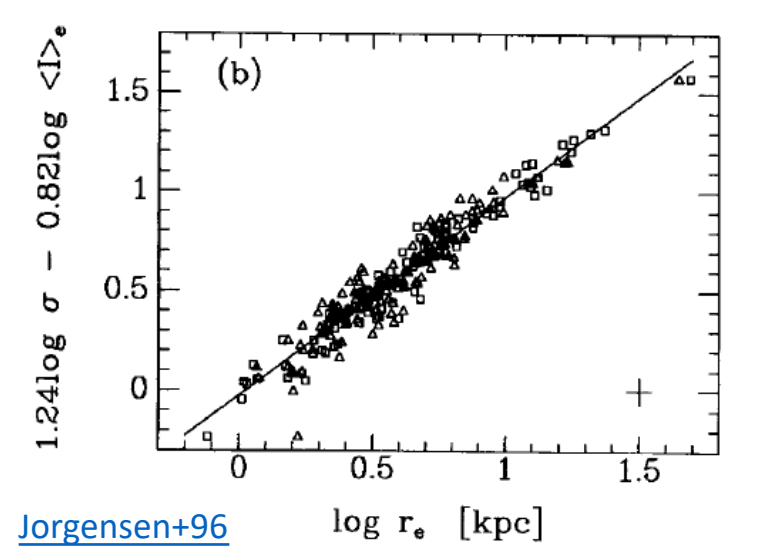
One axis always involves dynamical motion, which is determined by total mass (baryons + dark matter). If you know distance and understand stellar populations, you can constrain dark matter content.

Spirals:
Tully-Fisher



Sakai+ 00

Ellipticals:
Fundamental Plane

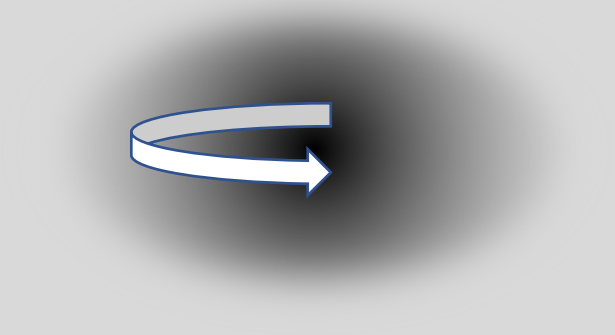


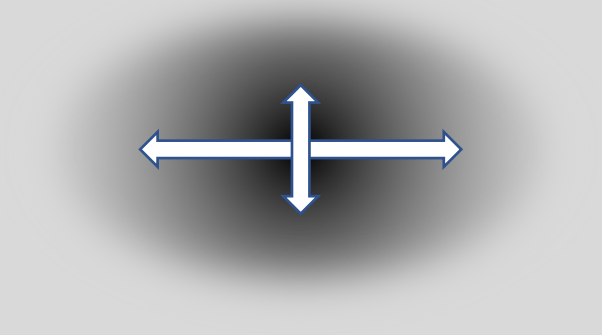
Jorgensen+96

Rotation vs Dispersion

Why are ellipticals flattened? Two possibilities:

- **Rotational support**: ellipticals are flattened due to relatively large spin (higher V_c/σ)
- **Pressure support**: ellipticals have higher velocity dispersion along one (or more) axes: $\sigma_x > \sigma_y$





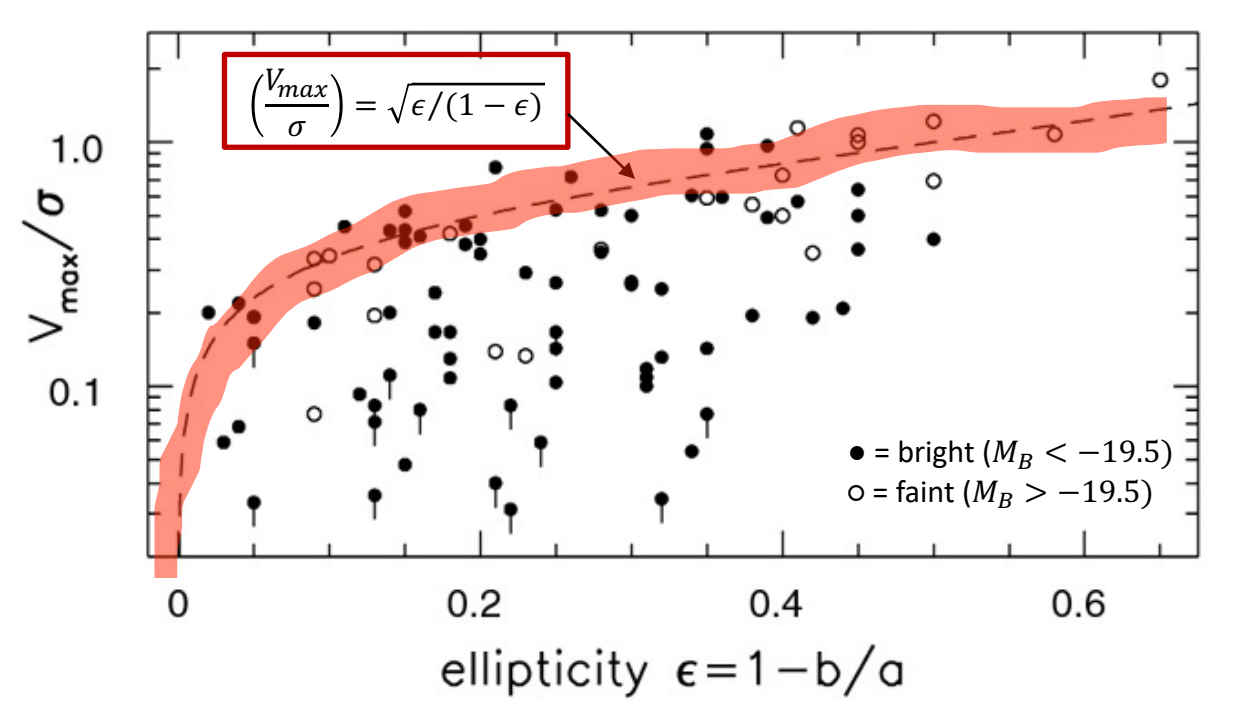
How could we tell?

Use the virial theorem* (connecting kinetic energy to potential energy) to derive a relationship between ellipticity (ϵ) and ratio of rotation to dispersion (V_{max}/σ):

$$\left(\frac{V_{max}}{\sigma}\right) \approx \sqrt{\epsilon/(1-\epsilon)}$$

If E's were flattened by rotation, they should follow this relationship.

(see Sparke & Gallagher text, Section 6.2.3)*

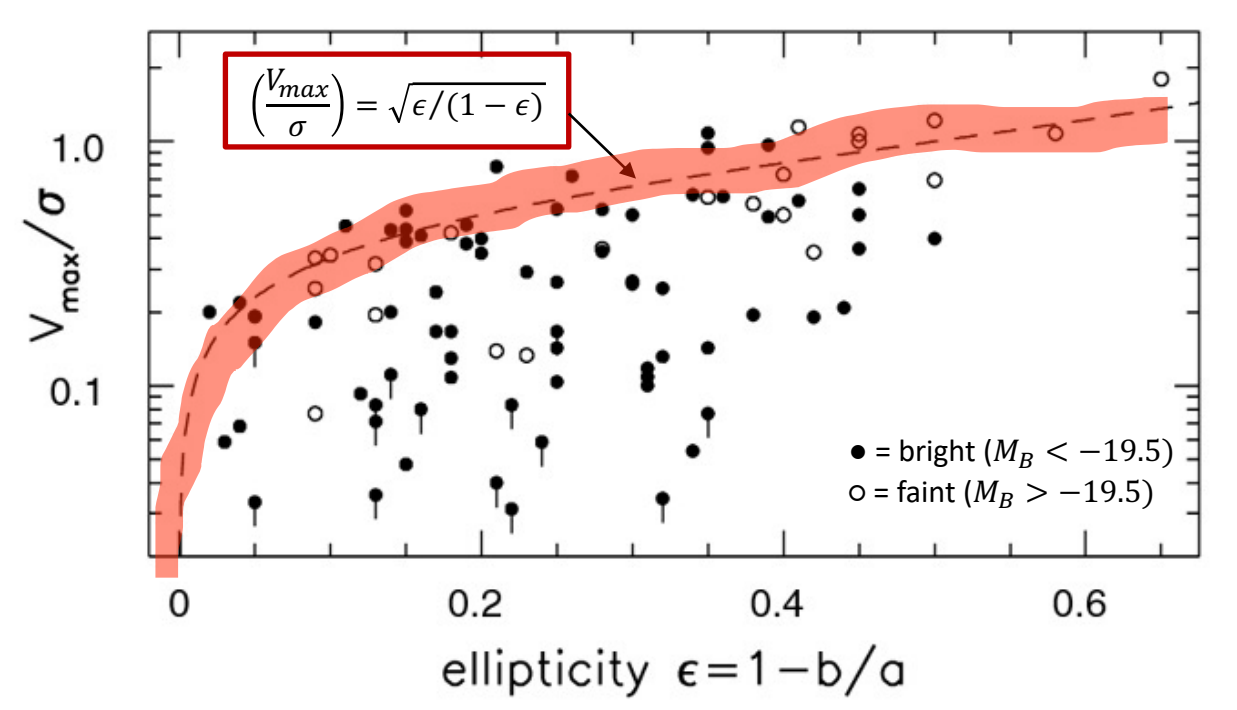


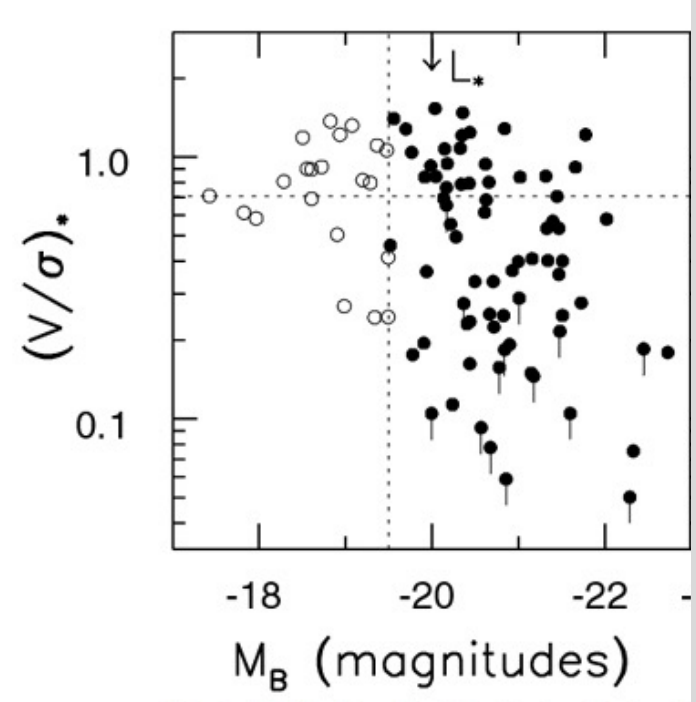
Rotation vs Dispersion

If we measure rotation, dispersion, and ellipticity, if ellipticals were flattened by rotation, they should follow the red/dashed line ⇒

Massive/luminous ellipticals generally rotate too slowly to be flattened by rotation. They are **pressure supported.**

Lower luminosity ellipticals are more likely to be (but not always) **rotationally supported**.





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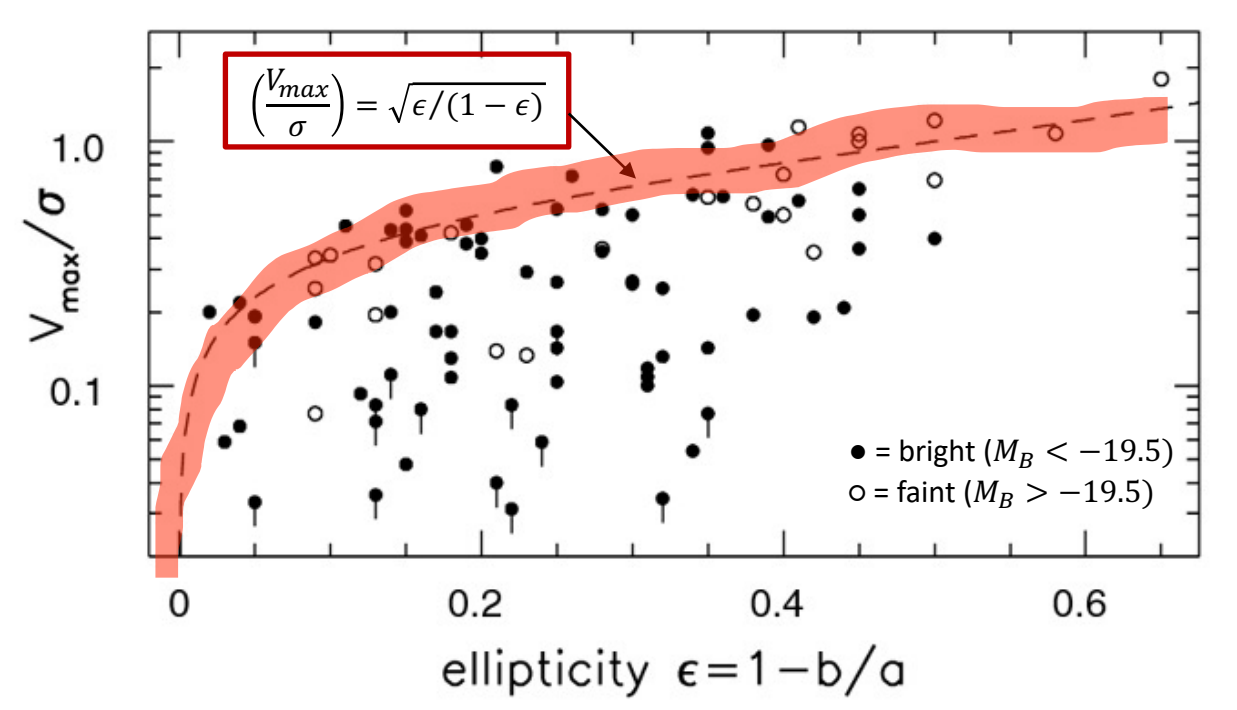
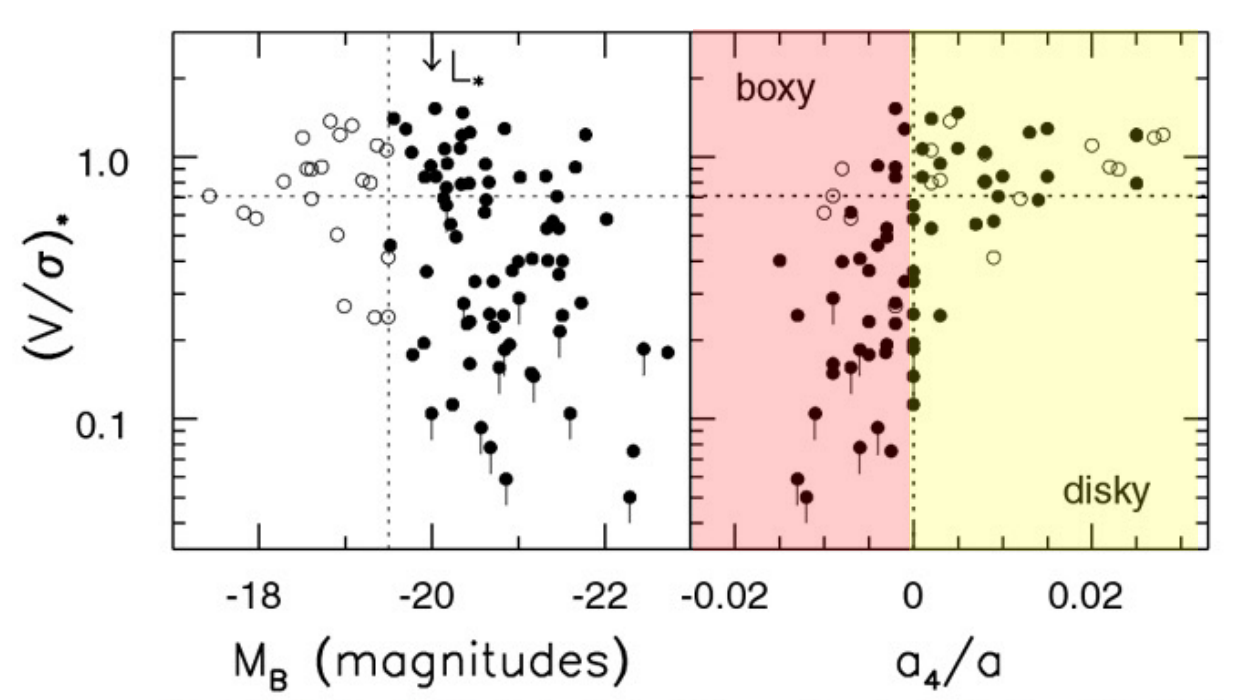


Boxy vs Disky

Slow rotators / high luminosity ellipticals tend to be boxy galaxies.

Fast rotators / lower luminosity ellipticals tend to be disky galaxies.

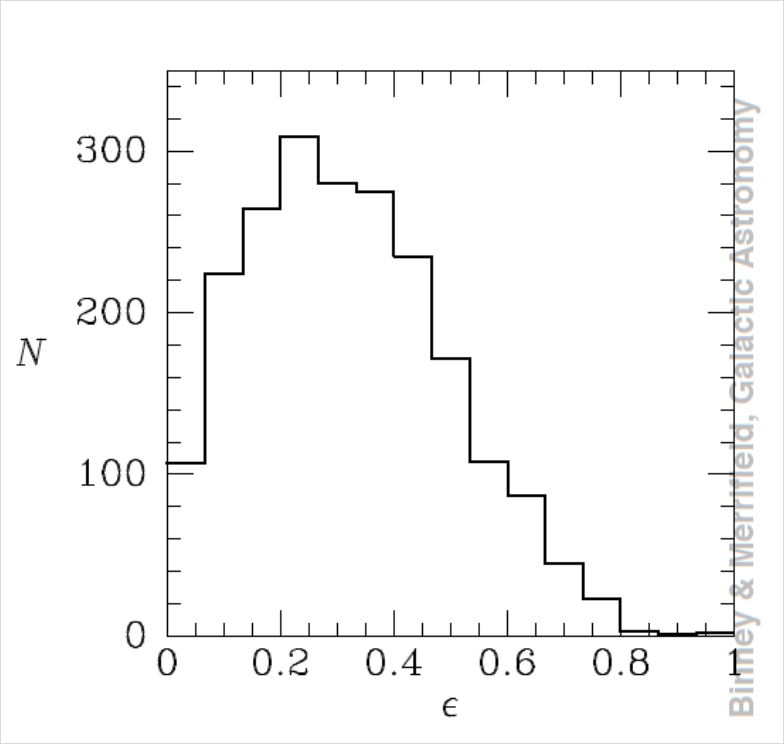
⇒ Different formation histories for low and high L ellipticals!



Intrinsic shapes of ellipticals

Cannot determine true axis ratios for any single galaxy, due to only seeing projected axis.

Need to do this statistically: adopt a model for true 3D axial ratios, model randomly projected shapes, adjust intrinsic shape model until real observations matched.



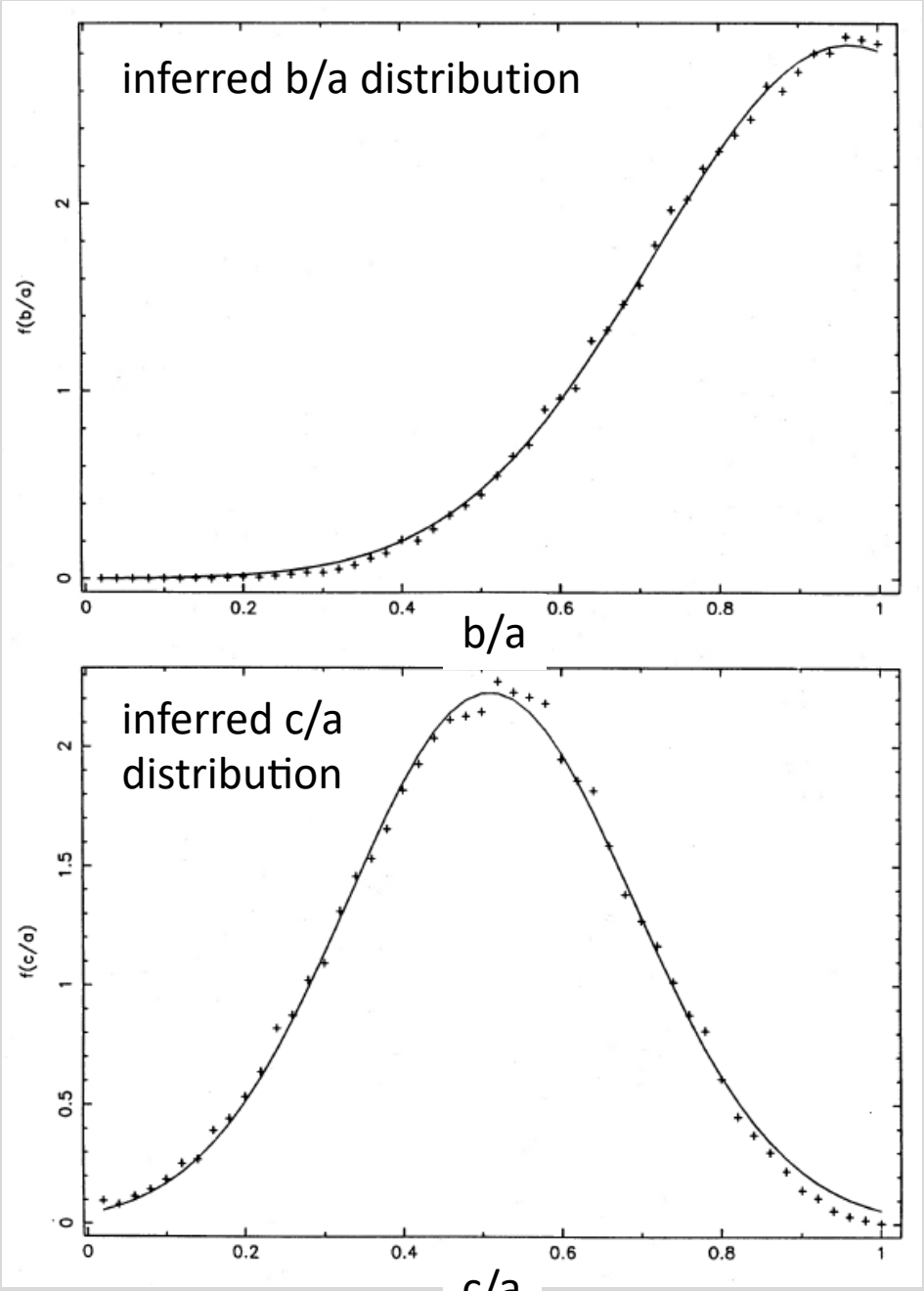
Observed shapes (1-b/a) of elliptical galaxies

Best fit by a mix of shapes, not purely oblate or prolate.

E's tend to be more oblate (🍔) than prolate (🏈).

But have a moderate amount of triaxiality.

Inferred **true** axis ratio distribution b/a, c/a: Lambas+92



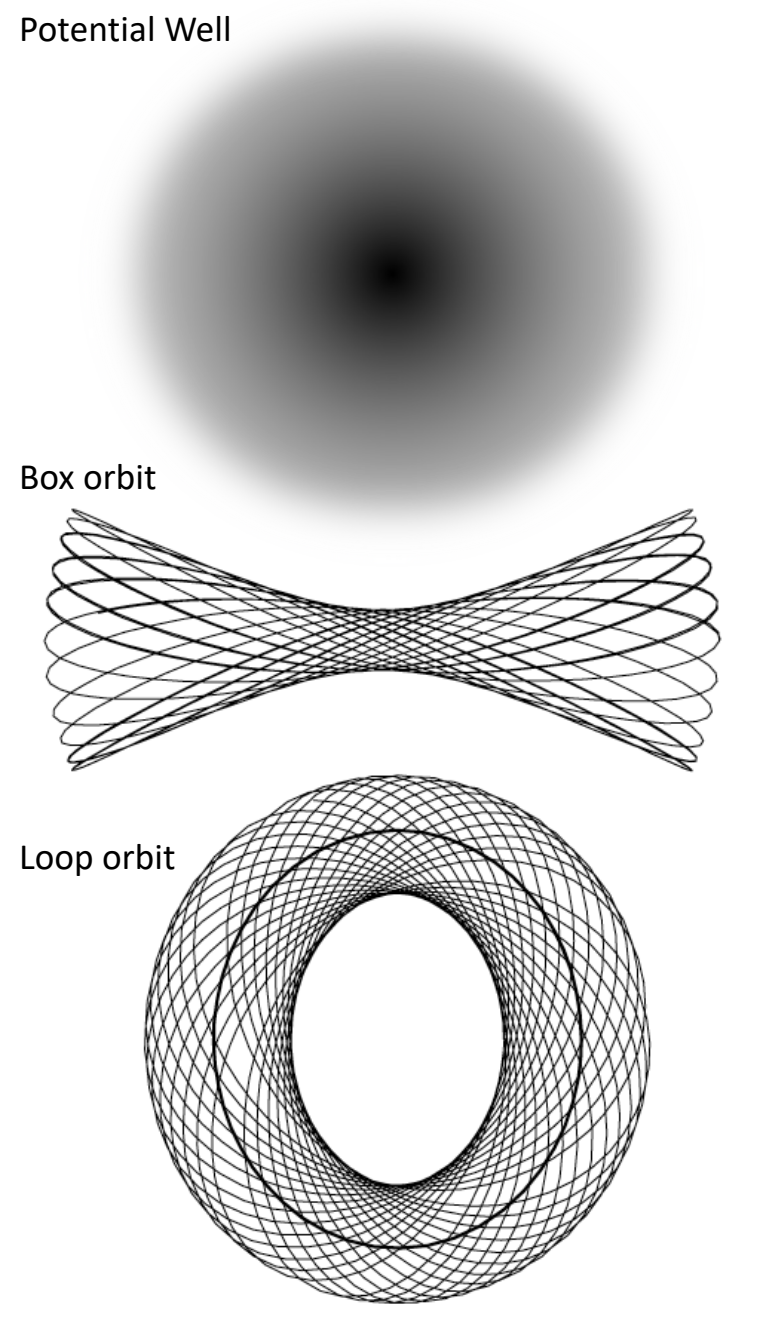
Orbits in elliptical galaxies

Recall disk galaxies: stars are on roughly circular orbits ($V_c/\sigma \gg 1$), and trace out rosette patterns on the disk plane.

Elliptical galaxies have low rotation, large random motions ($V_c/\sigma < 1$), and are mostly "pressure supported". What do the orbits look like?

Loop orbits: high angular momentum, avoid the center. Have a sense of rotation. Over time, the rosette boundaries will fill.

Box orbits: low angular momentum, pass arbitrarily close to the center. No net sense of angular momentum. Over time, the whole "pinched" rectangular-ish block will fill.



Orbits in 3D: Triaxiality

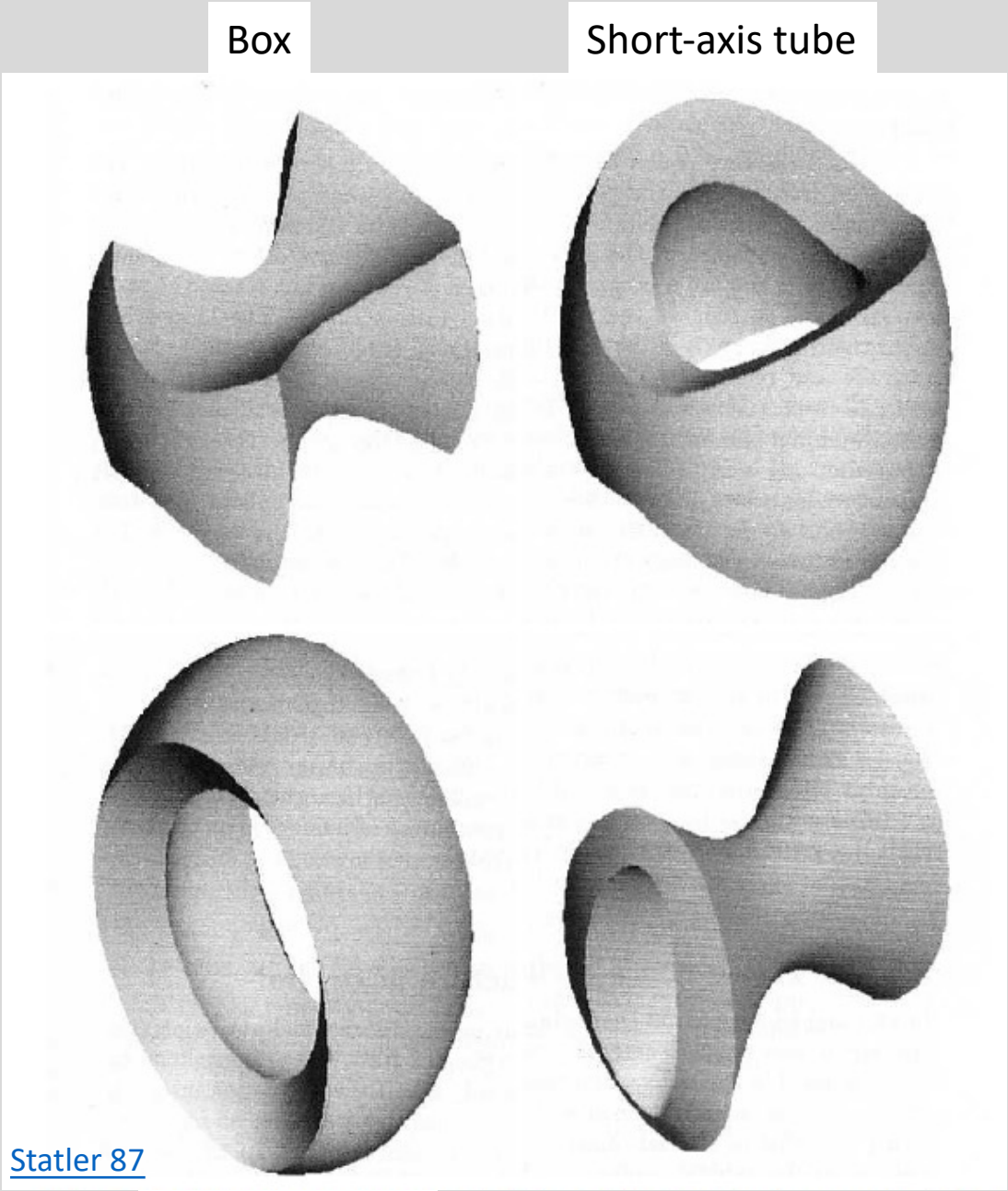
If the density of stars goes as $\rho(r) = \rho_0 (r_0/r)^\alpha$, then the radial force acting on a star goes as

$$F_r(r) = -\frac{GM(<r)}{r^2} \sim \frac{Gr^3\rho}{r^2} \sim r^{1-\alpha}$$

so if the density near the center increases more slowly than $\rho \sim r^{-1}$, then $F_r \to 0$ near the center and the potential acts like a harmonic oscillator independent in three directions. All box orbits.

Tube orbits are 3D loops. Long- and short-axis tubes are stable, intermediate-axis tubes are not.

Since tube orbits have axisymmetry, box orbits are the ones that sustain triaxiality.



Orbits in 3D: Triaxiality

If the density of stars rises near the center and goes as $\rho(r) = \rho_0 (r/r_0)^{-\alpha}$, then the radial force acting on a star goes as

$$F_r(r) = -\frac{GM(<r)}{r^2} \sim \frac{Gr^3\rho}{r^2} \sim r^{1-\alpha}$$

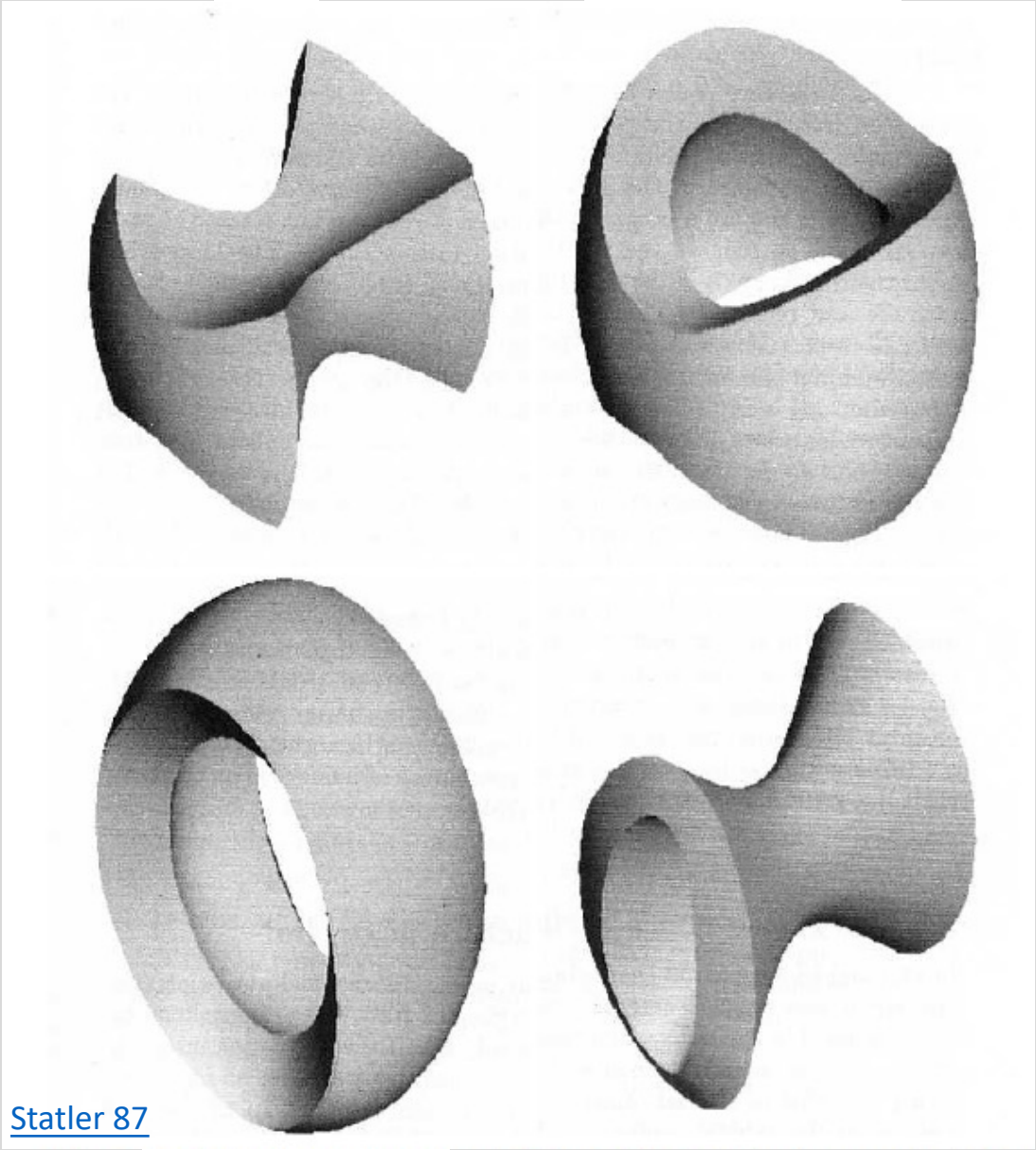
so if the density near the center increases more slowly than $\rho \sim r^{-1}$, then $F_r \to 0$ near the center and the potential acts like a harmonic oscillator independent in three directions. All box orbits.

Tube orbits are 3D loops. Long- and short-axis tubes are stable, intermediate-axis tubes are not.

Since tube orbits have axisymmetry, box orbits are the ones that sustain triaxiality.

Box

Short-axis tube



Statler 87

Long-axis tube

Inner Long-axis tube

Orbits and shapes

Remember:

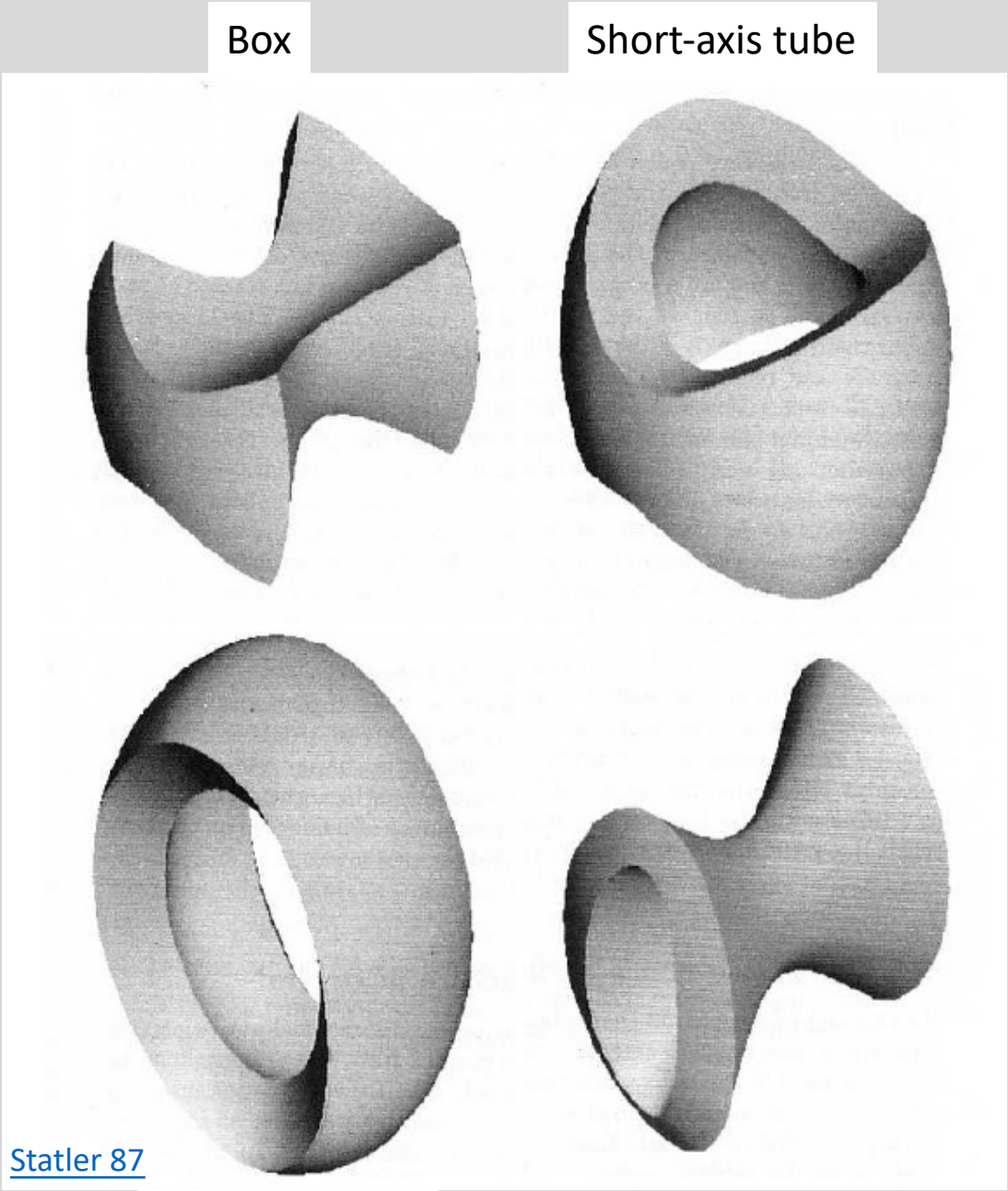
- A galaxy is made of stars.
- Where stars are is what sets the shape of the galaxy.
- The orbits set where the stars are.
- The stars set the potential (at least in the bright inner parts!)
- The potential (shape and radial profile) defines the orbit families.

So everything is interconnected. Change the potential, change the orbits, change the shape. Change the orbits, change the potential, change the shape....

If the density is much steeper than $\rho \sim r^{-1}$, orbits can be scattered off box orbits onto chaotic orbits.

- What could cause a very steep rise in density at the center?

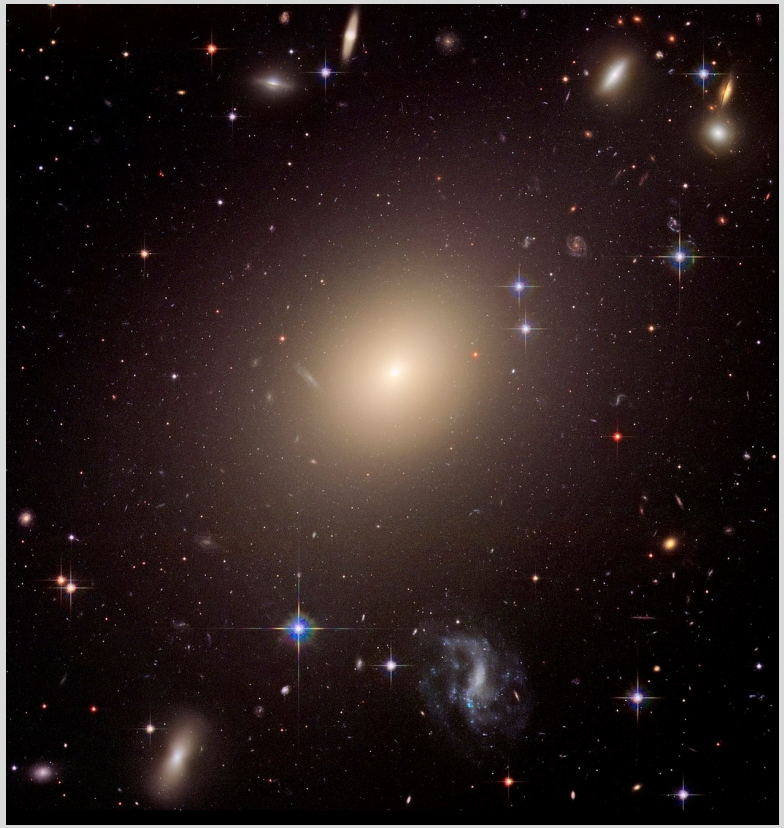
- What would happen to the shape if you scattered orbits?



Elliptical galaxies: dynamics and evolution

Stars form from cold gas. Where we see cold gas in galaxies, it is in thin rotating disks. If stars form from that gas, they should also be in disks.

Ellipticals aren’t like that; why are their stars moving so randomly?



Relaxation, or: how are orbits randomized?

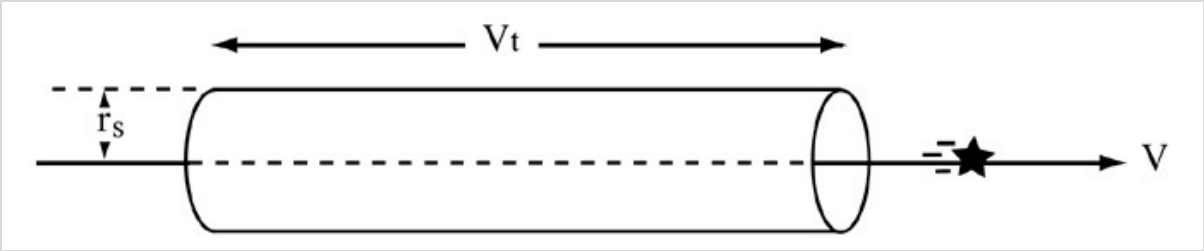
Relaxation: a process by which stars diffuse away from their initial orbits.

One relaxation process is **close encounters of stars**: close enough that the gravitational potential from the star is comparable to the kinetic energy of motion. For two stars of mass m, his gives a scattering radius (r_s) of

$$\frac{Gm^2}{r} \gtrsim \frac{1}{2}mV^2 \quad \Rightarrow \quad r_s \approx \frac{2Gm}{V^2} \approx 1\ AU$$

How often does this happen?

Over a time t, a star in motion will sweep out a cylinder of radius r_s that has a volume $\pi r_s^2 Vt$. If the density of stars per unit volume is given by n, then we would expect one encounter in a time where $n\pi r_s^2 Vt = 1$.



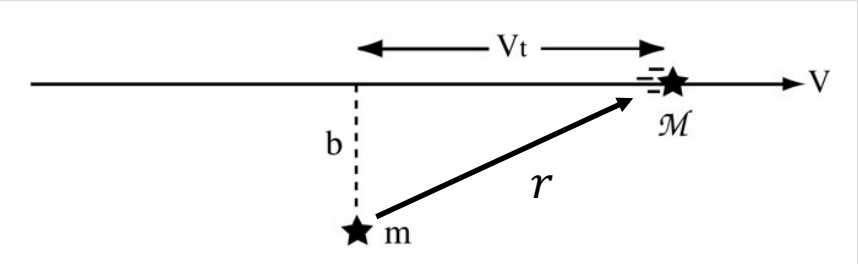
Thus the time between encounters is given by

$$t_s = \frac{1}{n\pi r_s^2 V} = \frac{V^3}{4\pi G^2 m^2 n} \approx 4\times10^{12}\ \mathrm{yr}\left(\frac{V}{10\ \mathrm{km/s}}\right)^3\left(\frac{m}{M_\odot}\right)^{-2}\left(\frac{n}{1\ \mathrm{pc}^{-3}}\right)^{-1}$$

This is much greater ($\approx 300\times$) than the age of the universe, so close encounters do not matter much.

Weak encounters (S&G 3.2.2)

What about the effect of many distant encounters continually nudging the star off its initial orbit? Consider a distant flyby of two stars at a distance b. The perpendicular force is given by



$$\vec{F}_\perp = \frac{GmM}{r^2}\left(\frac{b}{r}\right) = \frac{GmMb}{(b^2+V^2t^2)^{3/2}} = M\frac{d\vec{V}_\perp}{dt}$$

Integrate this over time to get

$$\Delta V_\perp = \frac{1}{M}\int_{-\infty}^{\infty}\vec{F}_\perp(t)dt = \frac{2Gm}{bV}$$

So the star is deflected through a (small) angle $\alpha = \frac{\Delta V_\perp}{V} = \frac{2Gm}{bV^2}$

Over time, the star will experience many weak deflections, which gives rise to a squared velocity change of

$$\langle \Delta V_\perp{}^2 \rangle = \int_{b_{min}}^{b_{max}} \boxed{nVt}\boxed{\left(\frac{2Gm}{bV}\right)^2}\boxed{2\pi b\, db} = \frac{8\pi G^2 m^2 nt}{V}\boxed{\ln\left(\frac{b_{max}}{b_{min}}\right)}$$

number of encounters
scattering per encounter
probability of encounter
the "Coulomb logarithm"

$$\ln\left(\frac{b_{max}}{b_{min}}\right) \equiv \ln\Lambda$$

Relaxation time: where $\langle \Delta V_\perp{}^2 \rangle = V^2$. So

$$t_{relax} = \frac{V^3}{8\pi G^2 m^2 n \ln\Lambda} = \frac{2\times10^{12}\ \mathrm{yr}}{\ln\Lambda}\left(\frac{V}{10\ \mathrm{km/s}}\right)^3\left(\frac{m}{M_\odot}\right)^{-2}\left(\frac{n}{1\ \mathrm{pc}^{-3}}\right)^{-1}$$

Weak encounters (S&G 3.2.2)

$$t_{relax} = \frac{2\times10^{12}\ \mathrm{yr}}{\ln\Lambda}\left(\frac{V}{10\ \mathrm{km/s}}\right)^3\left(\frac{m}{M_\odot}\right)^{-2}\left(\frac{n}{1\ \mathrm{pc}^{-3}}\right)^{-1}$$

So what about this pesky Coulomb logarithm?

$$\ln\Lambda \equiv \ln\left(\frac{b_{max}}{b_{min}}\right)$$

b_{min}: close scattering radius, $r_s \approx 1AU$
b_{max}: size of the stellar system. ≈ 300 pc – 30 kpc, depending on what kind of galaxy (dwarf, giant?)

so $\ln\Lambda \approx 18 - 22$. Exact value doesn't matter. Diffusion of orbits will still be very slow, occurring over 100 billion year timescales. Again, this is $\approx 10\times$ the age of the universe.

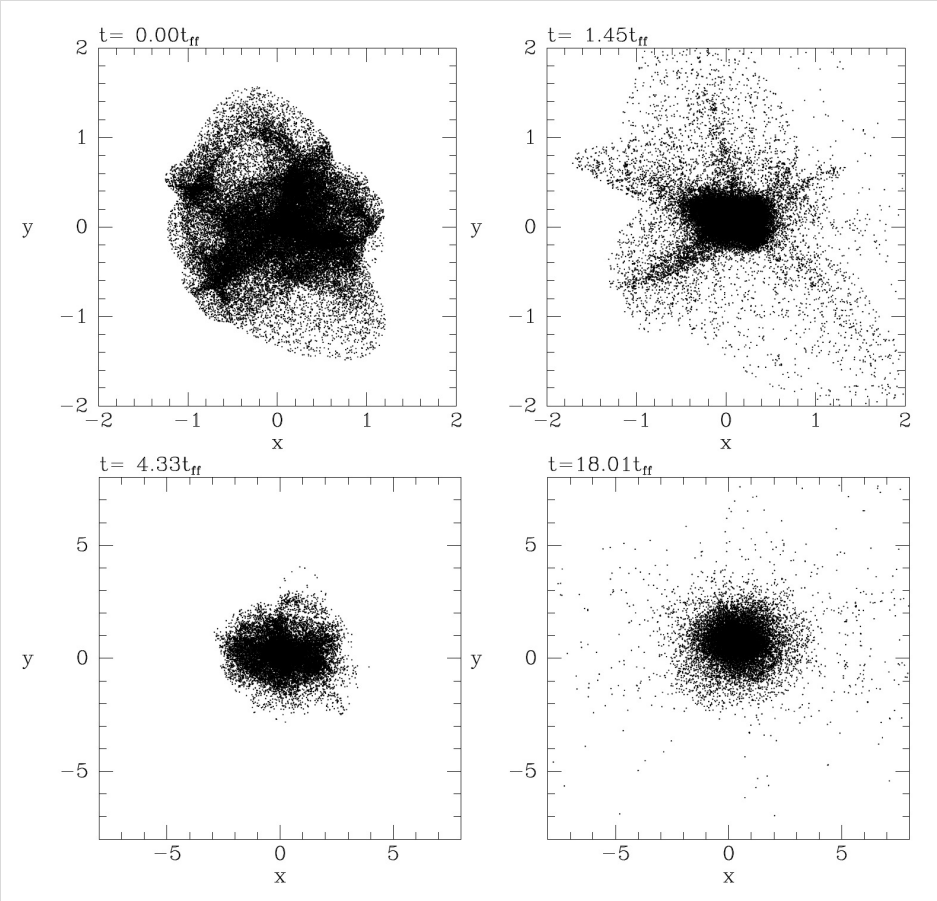
Upshot: In galaxies, scattering of stars by other stars are (statistically) unimportant. **Galaxies are "collisionless".**

So why are elliptical galaxies so disordered?

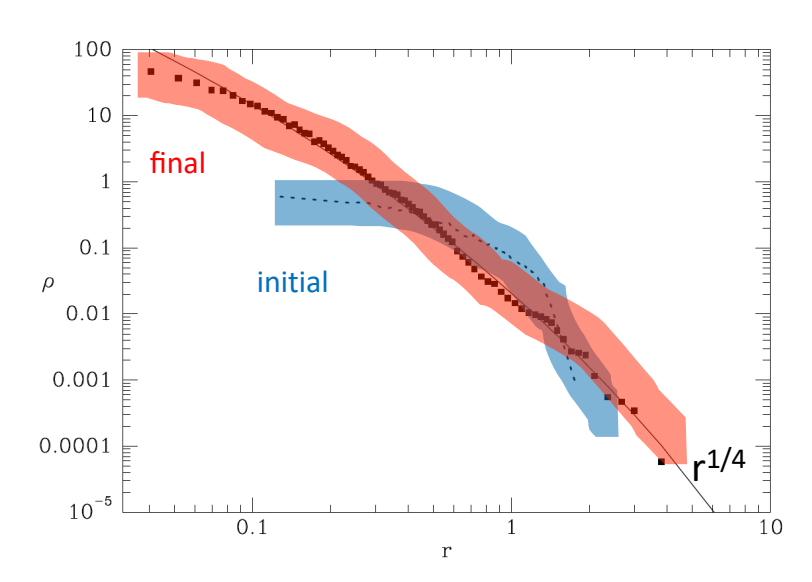
Violent relaxation

All these calculations rely on conservation of energy along the orbit. But if the potential well changes with time, energy cannot be conserved, because $E = \frac{1}{2}v^2 + \phi(\vec{x}, t)$. Changing potential ⇒ changing energy ⇒ randomization of orbits

Look at simulations of gravitational collapse. Start with a spherical roughly constant density distribution of stars, perturb them slightly, and then let gravity do its thing.



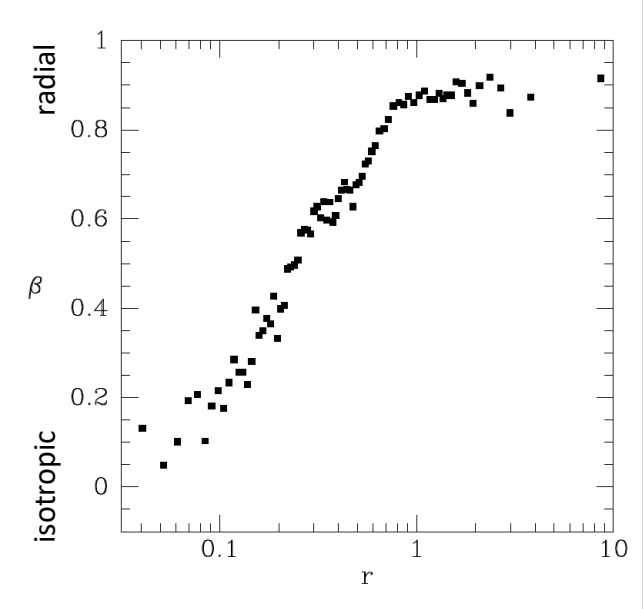
Density profile



↑ $r^{1/4}$-like density profile...

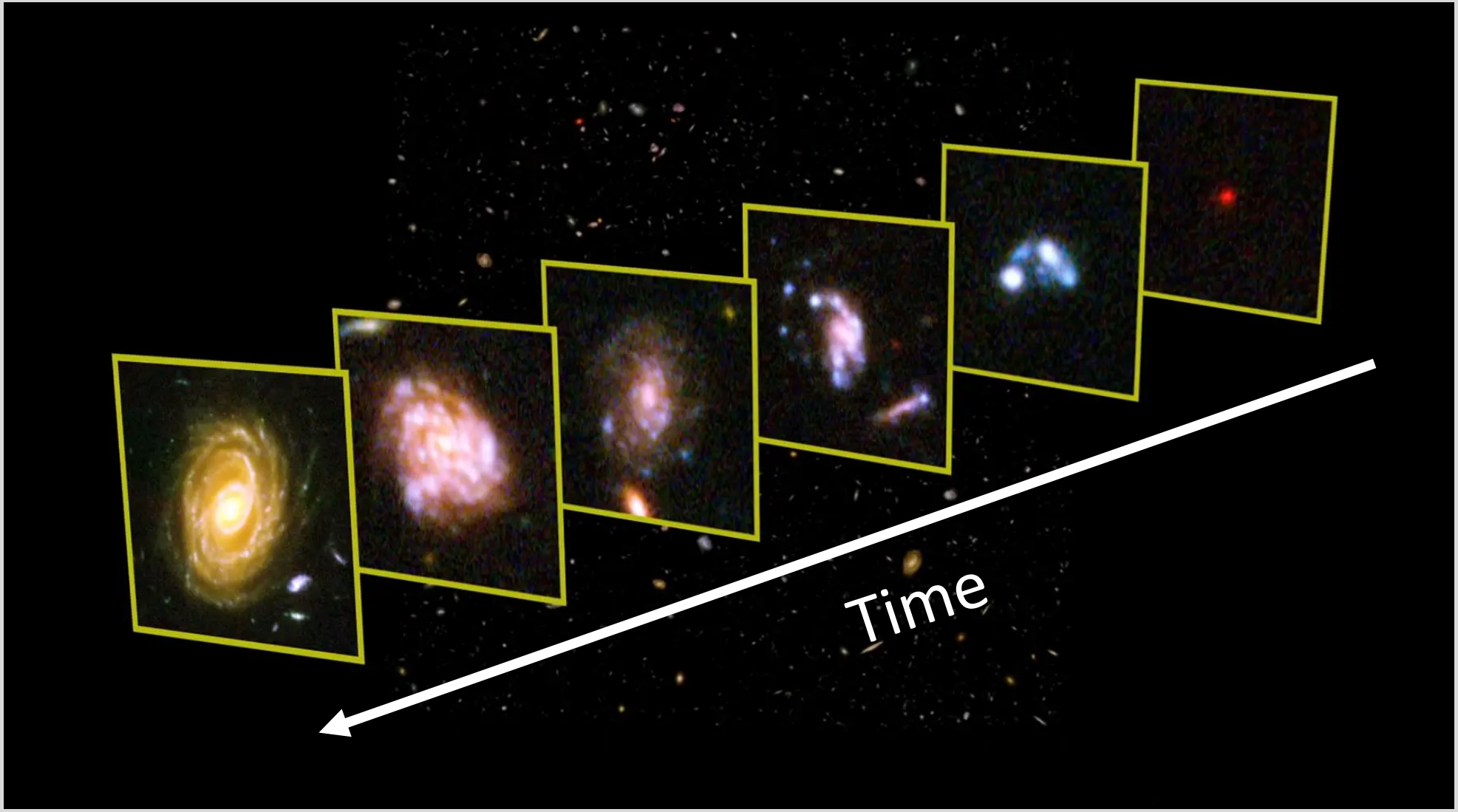
...with radially-biased anisotropy →

Velocity anisotropy



Violent relaxation

Hierarchical growth of galaxies (small things mergering to make big things) is one example of the violent relaxation process.



Violent relaxation

Galaxy mergers are another example of the violent relaxation process.

Black Holes

Centers of galaxies often have supermassive black holes ($M_{BH} \sim 10^6 - \text{few} \times 10^9 M_\odot$). How can we detect these objects?

"Sphere of Influence": where the circular velocity around a black holes is comparable to the velocity dispersion of the surrounding stars:

$$V_{c,BH}^2 = \frac{GM_{BH}}{r} \approx \sigma^2$$

or

$$r_{BH} \approx \frac{GM_{BH}}{\sigma^2} \approx 45 \left(\frac{M_{BH}}{10^8 M_\odot}\right)\left(\frac{\sigma}{100\ \text{km/s}}\right)^{-2} \text{pc}$$

Inside this radius, the gravitational influence of the black hole should begin to dominate stellar velocities, and we should see a signature in the kinematics.

Example: NGC 1399 (Fornax)

- $\sigma = 350$ km/s, $M_{BH} = 10^9 M_\odot, r_{BH} \approx 36$ pc.
- At d=20 Mpc, this is an angular size of 0.4 arcsec.
- Need Hubble or ground-based adaptive optics!

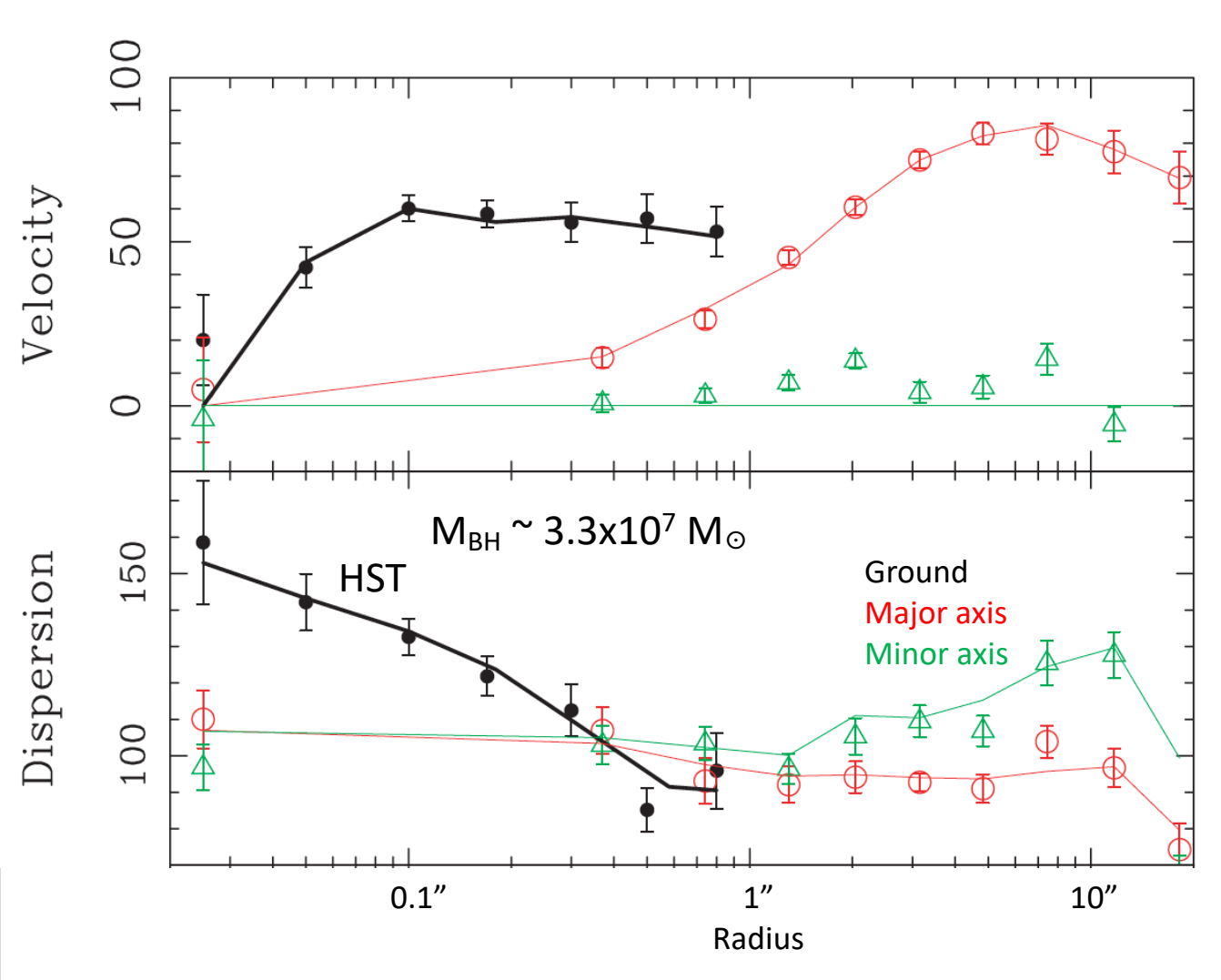
Measure via stellar kinematics

Rising velocity dispersion near center.

Must be careful to distinguish between gravitational effects of a black hole and the signature of radial anisotropy.

NGC 4258

NGC 4258 Siopis+09

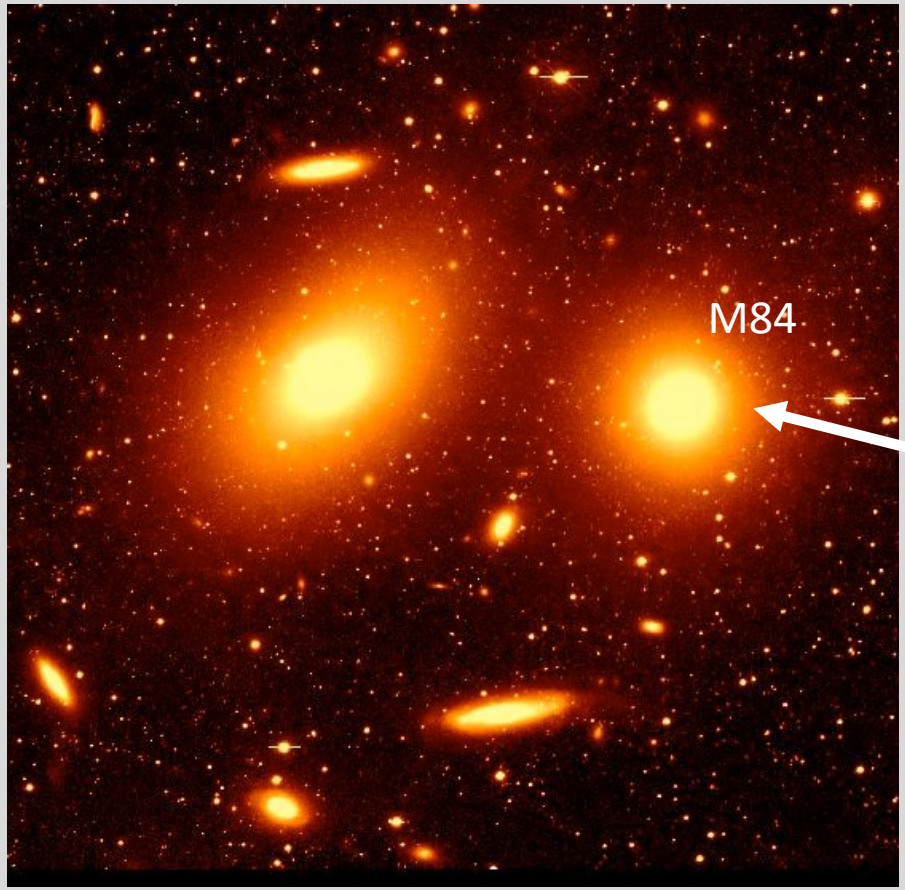


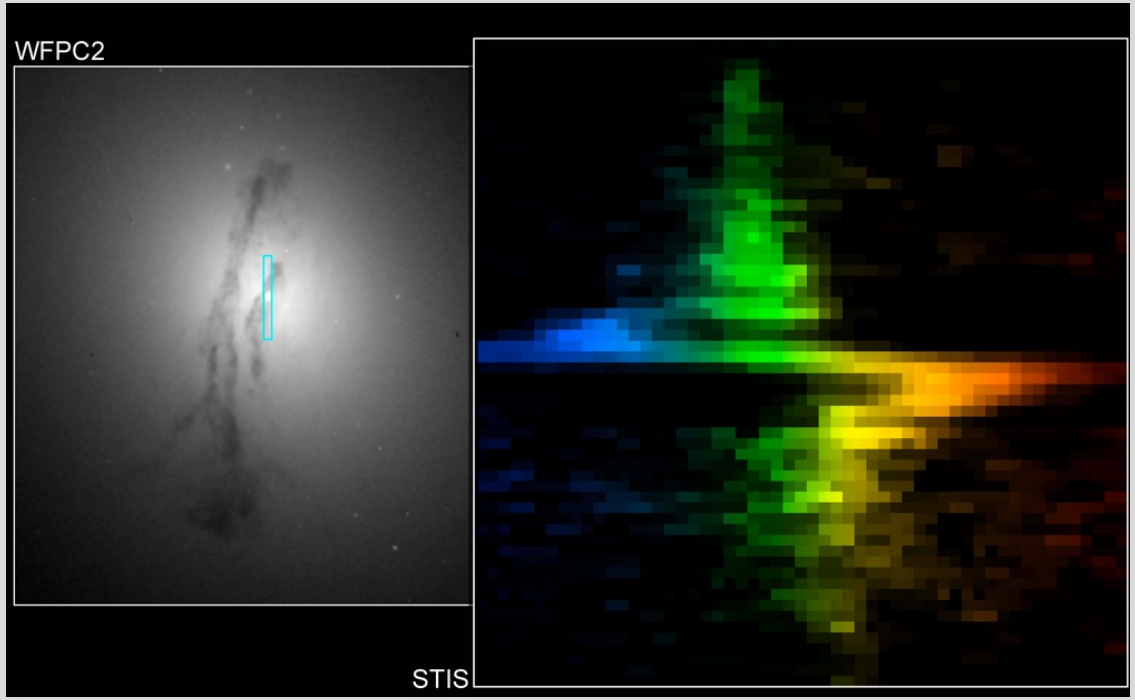
Note logarithmic scale on radius!

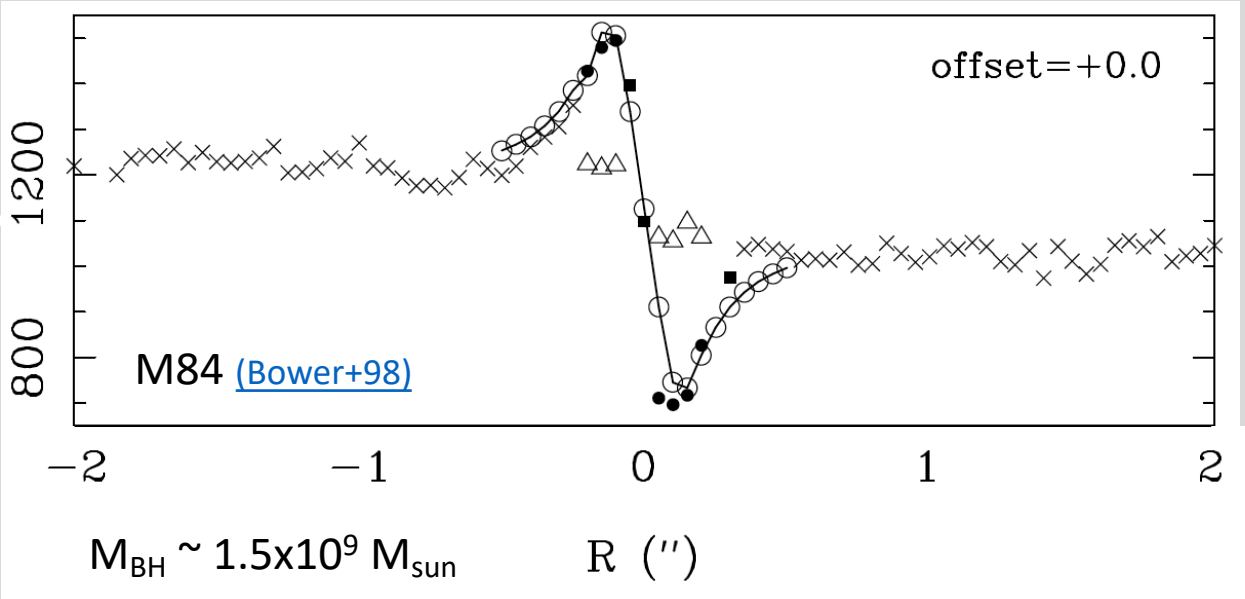
Measure via gas kinematics

Gas orbiting around the black hole shows rising circular velocity near center. *(Note: this is on scales much larger than the BH accretion disk!)*

Have to factor in the inclination of the disk.







$M_{BH} \sim 1.5 \times 10^9\ M_{sun}$

Black Holes

Black hole mass strongly tied to bulge mass, where "bulge" means

- spiral bulge, or
- elliptical galaxy

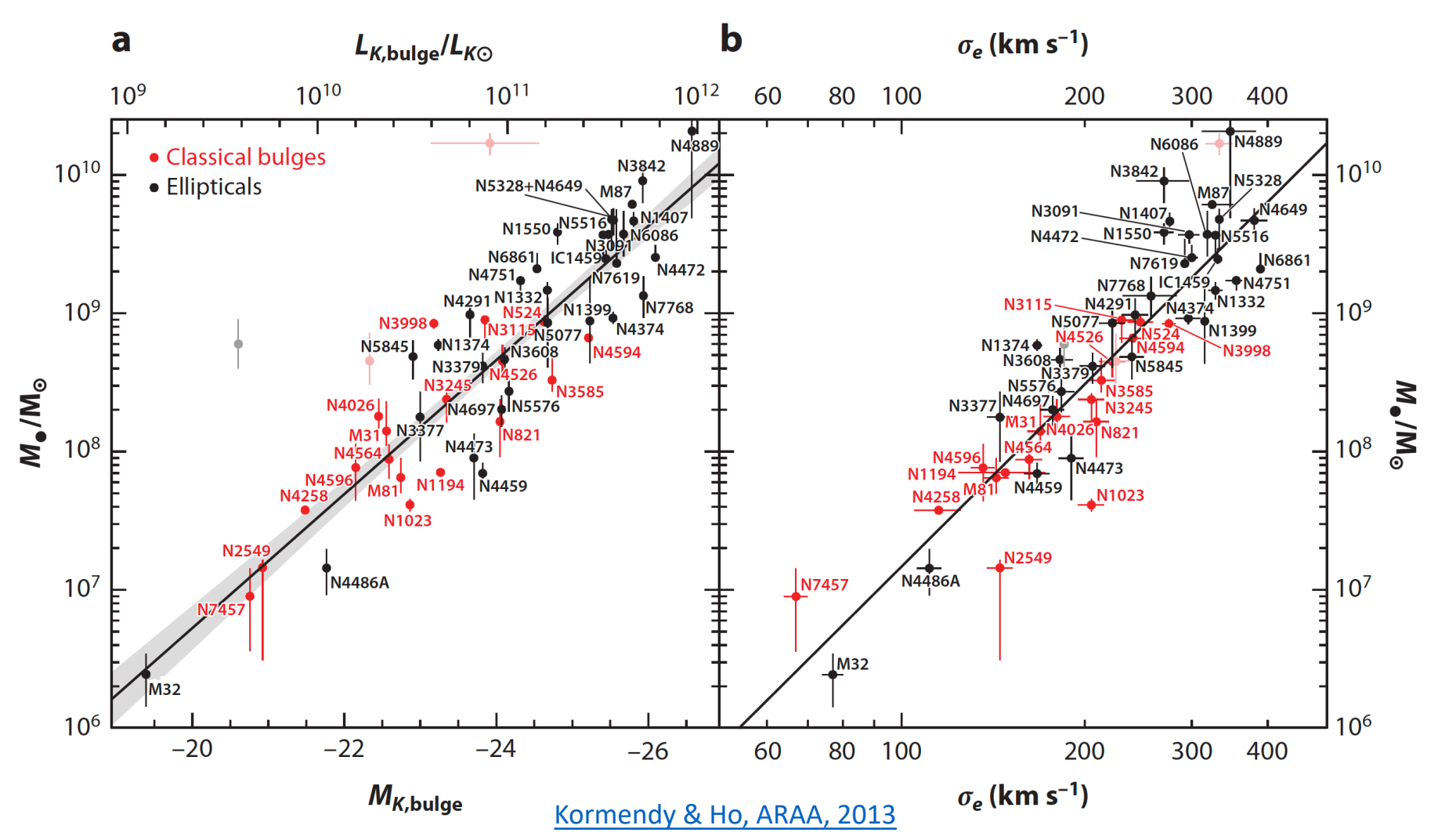
Both relations show a scatter in log(M_{BH}) of ~ 0.3, or a factor of two in mass.

Correlation with luminosity:

$$M_{BH} \sim L_{K,bulge}^{1.2}$$

Correlation with velocity dispersion:

$$M_{BH} \sim \sigma_e^{4.4}$$

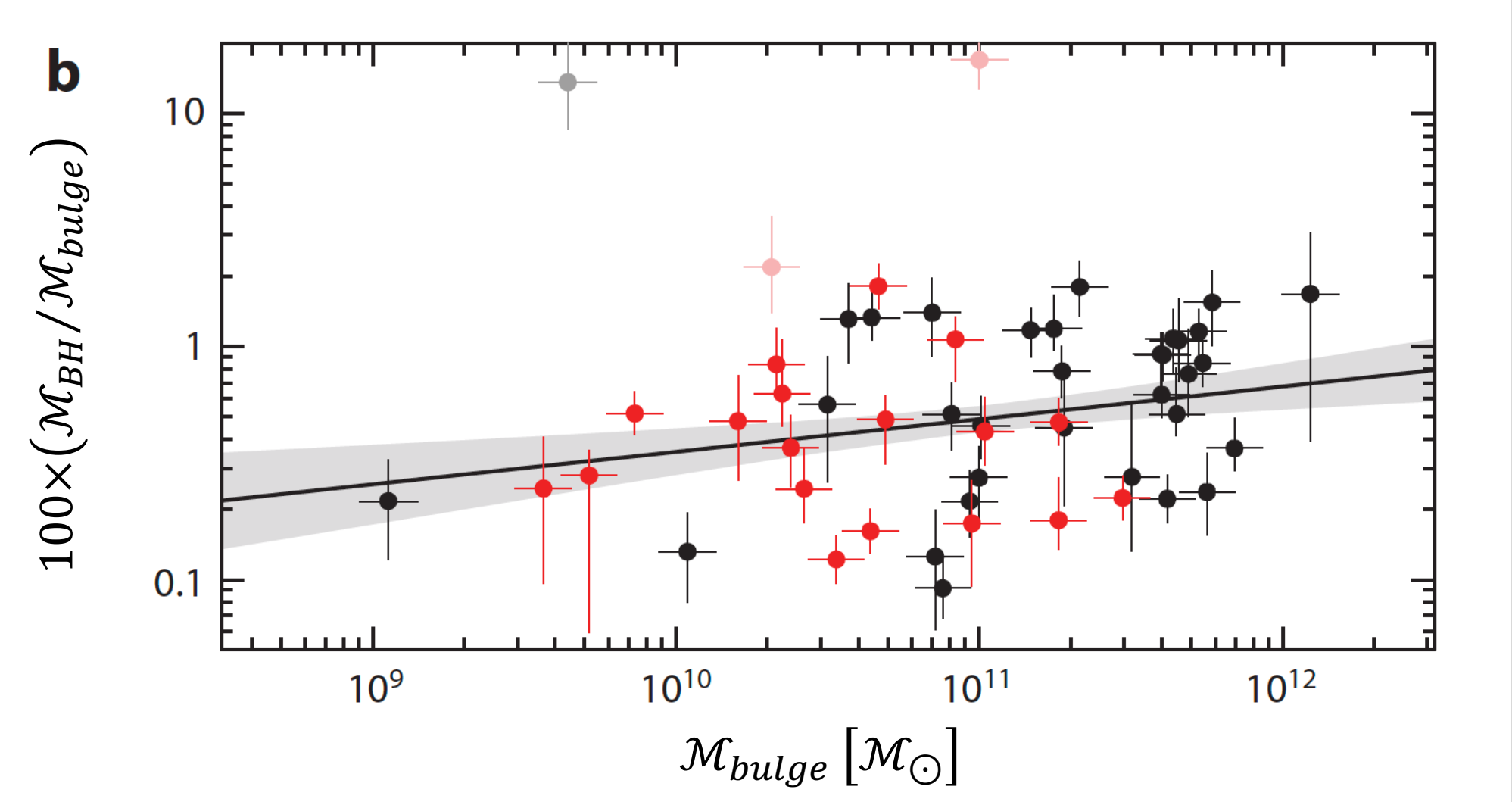


Kormendy & Ho, ARAA, 2013

Black Holes

Kormendy & Ho, ARAA, 2013

Black hole masses are generally **0.1–1%** of the “bulge” mass.



Black Holes

Black hole mass ***not*** coupled to disk mass.

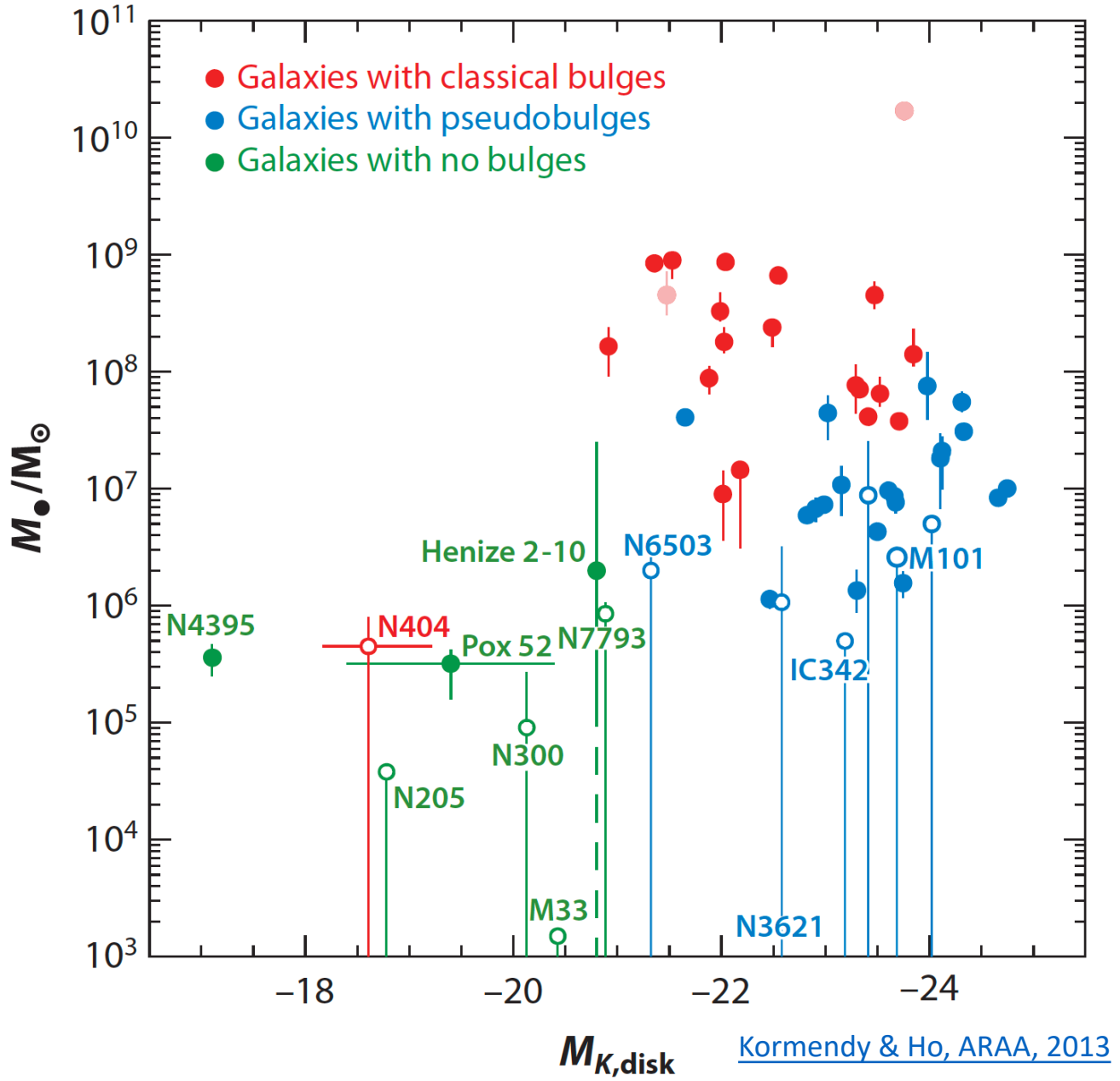
So the coupling is not with the properties of the galaxy, but the properties of the bulge.

"**coevolutionary**": whatever forms/grows the bulge also forms/grows the black hole.

Disks are a passive player in this evolution.

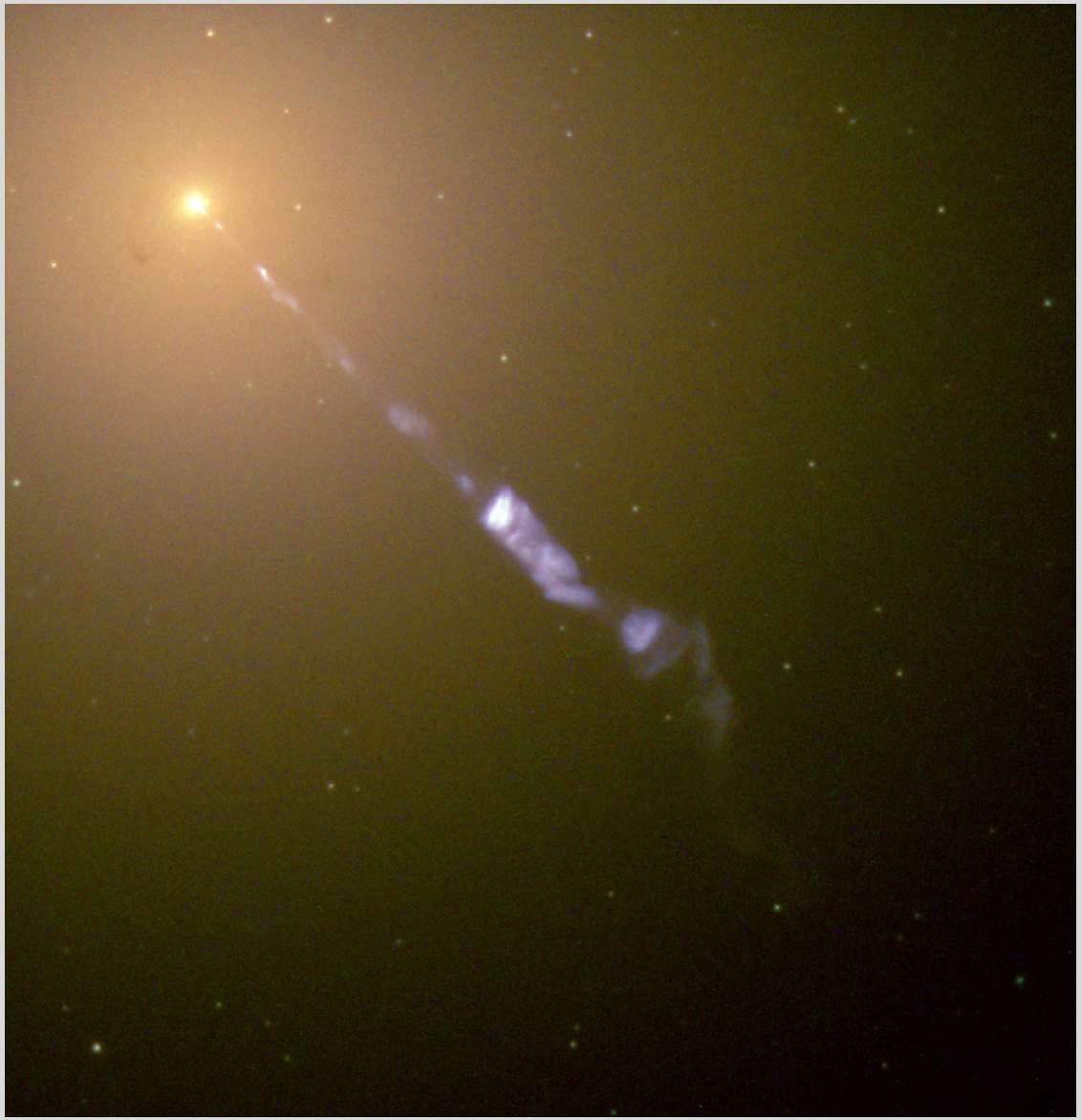
remember for spirals:

- "classical bulge" = $r^{1/4}$-ish spheroidal bulge
- "pseudobulge" = disky/exponential bulge



Kormendy & Ho, ARAA, 2013

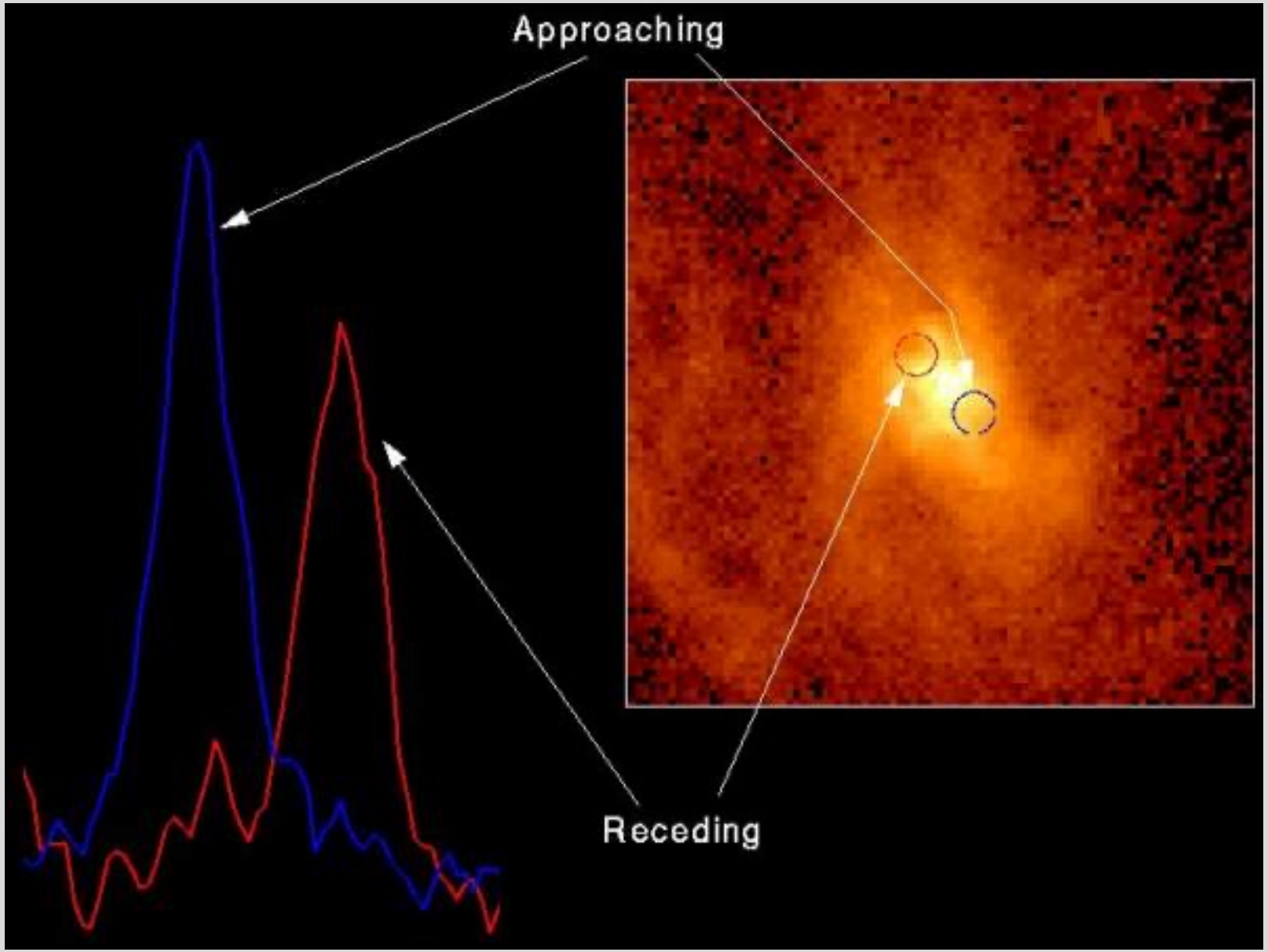
M87
Virgo elliptical
D=16.5 Mpc



M87

Gas kinematics near the center:

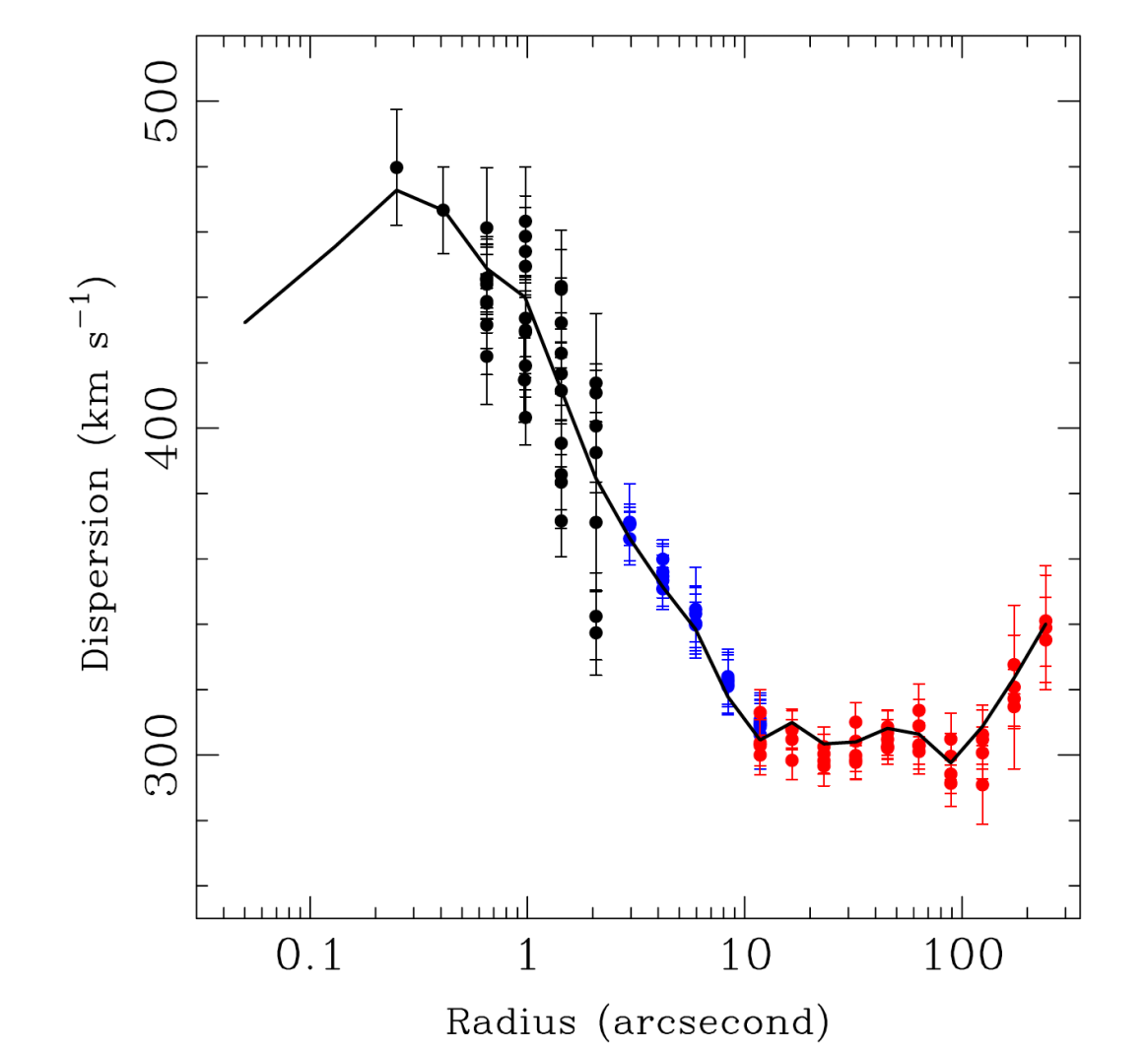
$M_{BH} \approx 3.5 \times 10^9\ M_\odot$ (Walsh+13)



M87

Stellar kinematics near the center:

$M_{BH} \approx 6.6 \times 10^9\ M_\odot$ (Gebhardt+11)



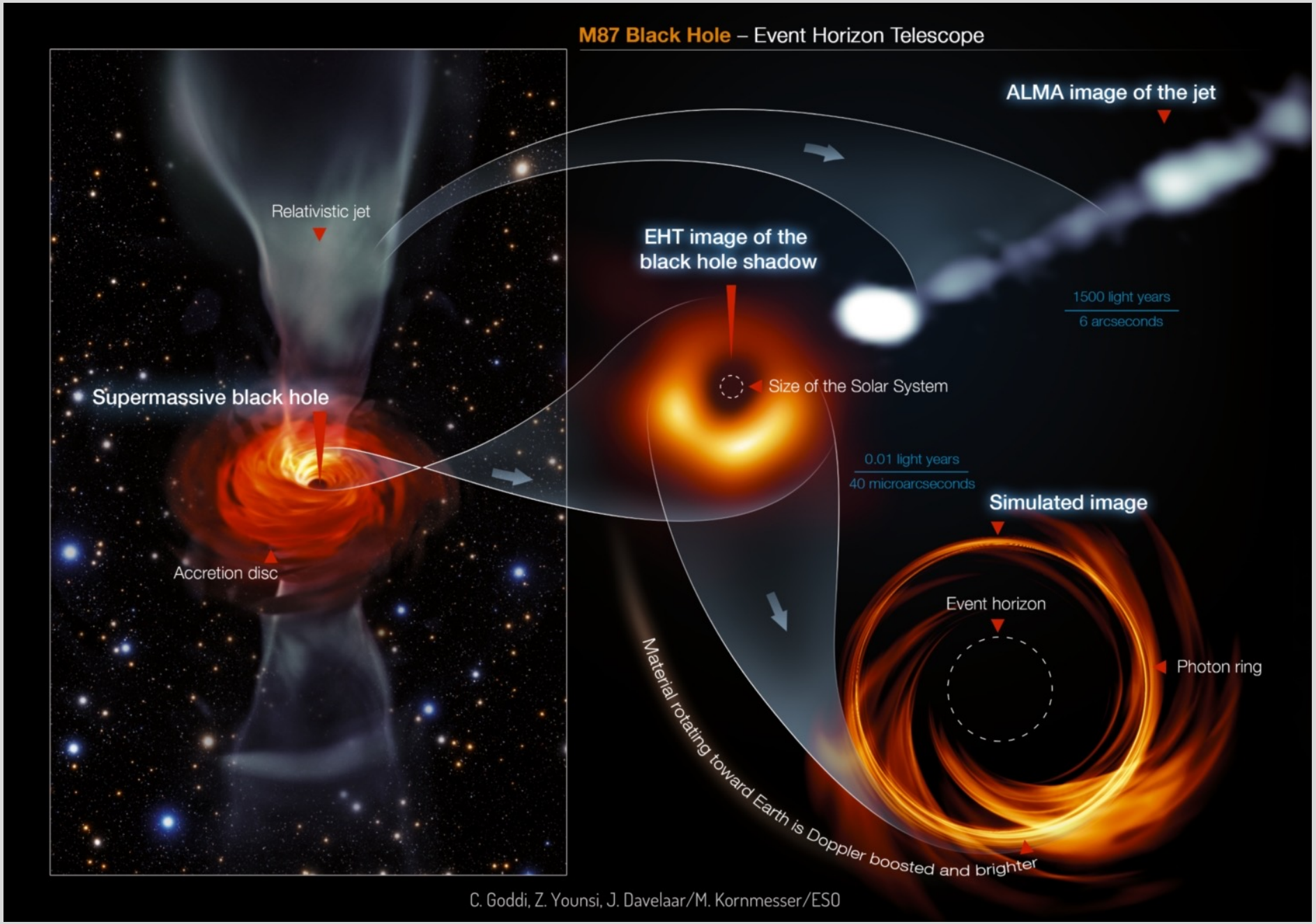
M87

The event horizon of the black hole is extremely small at the distance of M87:

$$R_s \equiv \frac{2GM_{BH}}{c^2}$$
$$\approx 3-6 \times 10^{-4}\ \mathrm{pc}$$
$$\theta = 4-8 \times 10^{-6}\ \mathrm{arcsec}$$

Event Horizon Telescope: world-wide array of radio telescopes doing radio interferometry of the hot gas around the black hole.

[EHTC 2019]



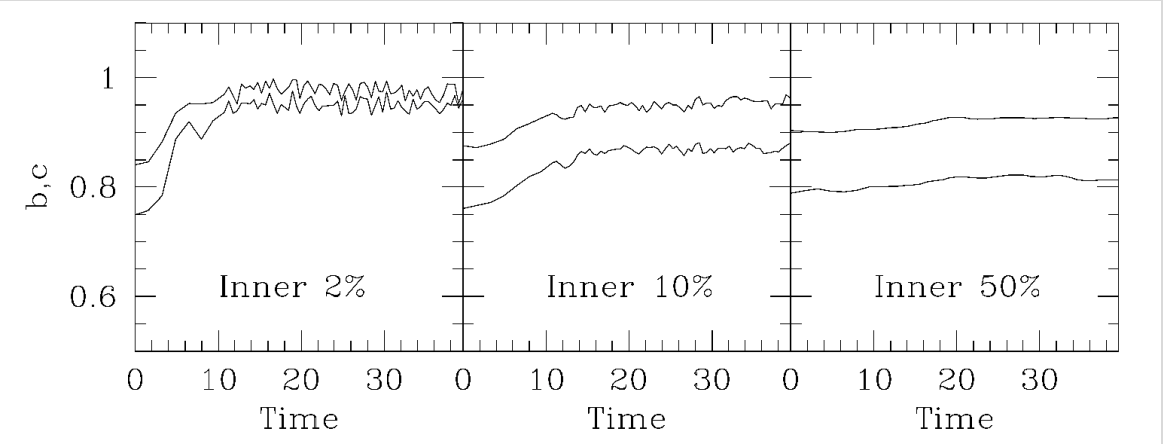
The effect of black holes

Black holes accrete matter and drive active galactic nuclei (AGN). They also inject energy into the interstellar medium via photoionization and shocks. But what do they do to the distribution of stars?

Black holes scatter stars off box orbits: erode triaxiality.

Simulation 👉: Grow 1% mass black hole in nucleus of triaxial galaxy model (a=1, b=0.85, c=0.75). Box orbits become chaotic and isotropic. Inner regions get rounder. Important for nucleus, less so for bulk of galaxy.

Holley-Bockelmann +02



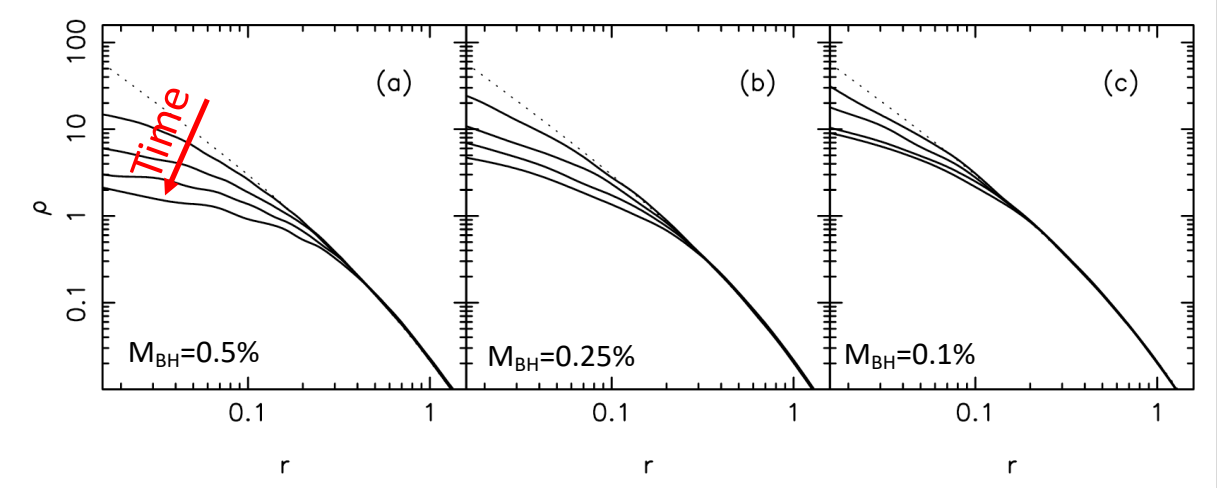
Binary black holes: "scour nucleus", reduce central density.

Stars interact with binary black hole, gain energy, get ejected from nucleus. Black hole binary loses energy, binary gets closer ("hardens") eventually merges.

Question: Why would there be a binary black hole?

Simulation👉: Multiple BH binary events.

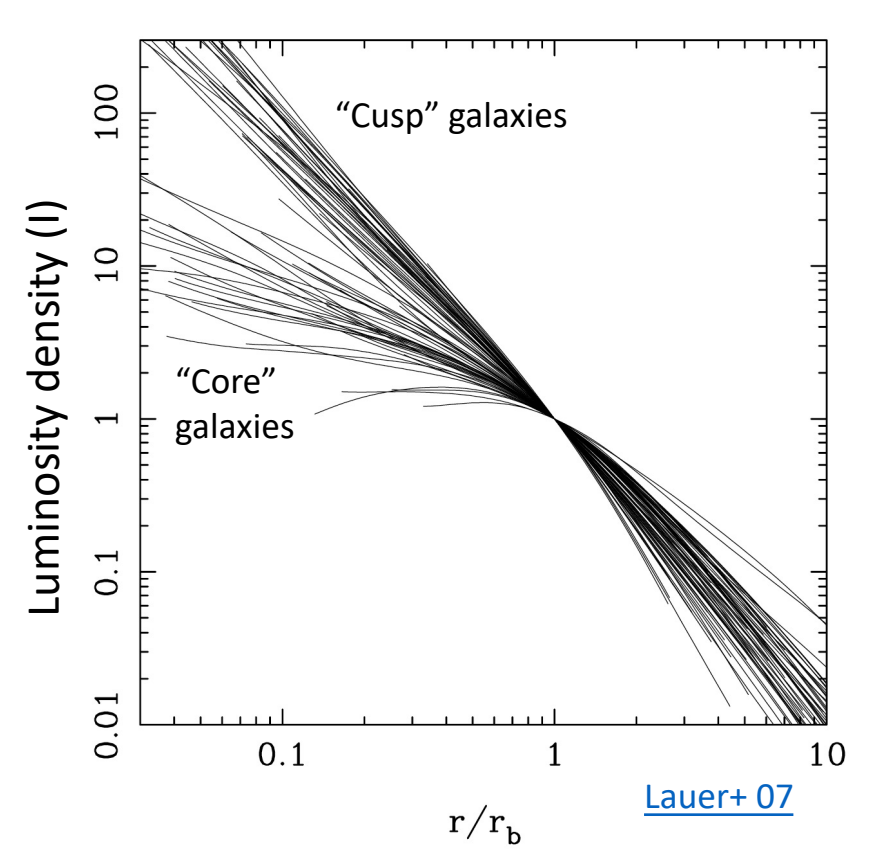
Merritt 06

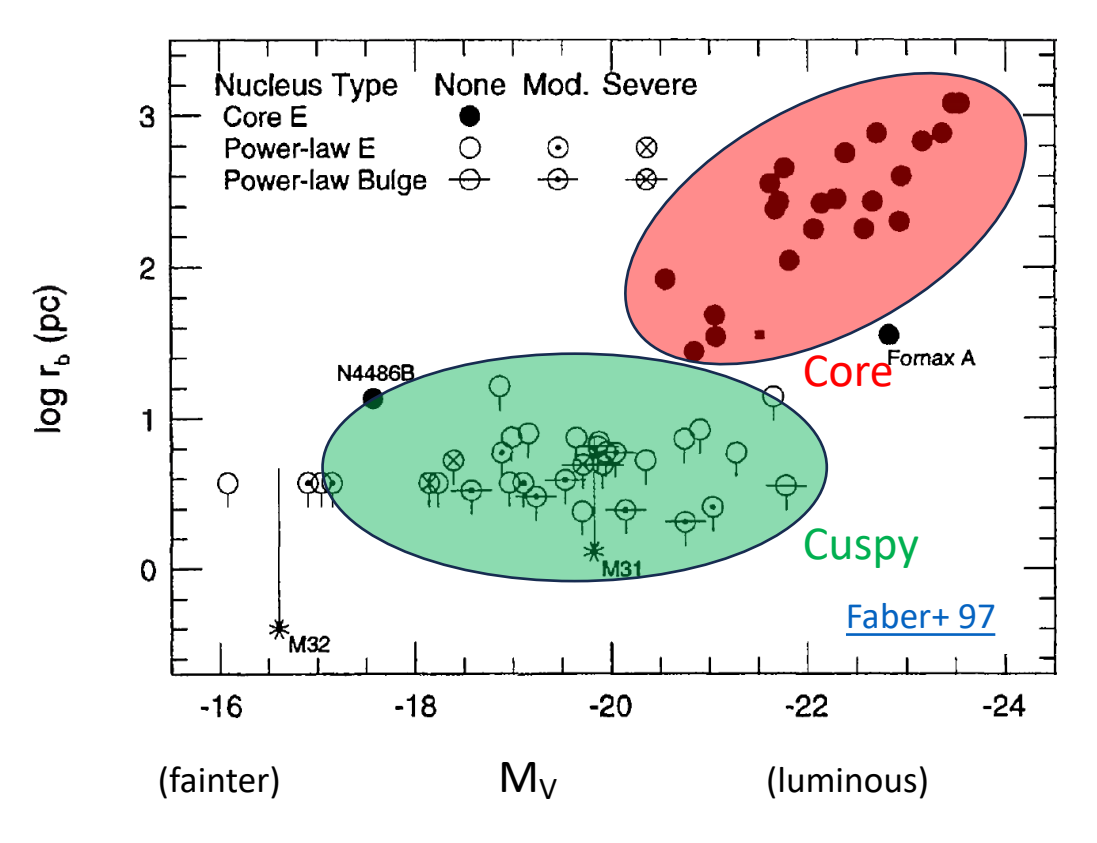


Nuclei of elliptical galaxies: cusp/core profiles

HST studies of the nuclear surface brightness profiles of ellipticals show evidence for "cusp/core" dichotomy.

At small radius, the profile often shows a break from the outer profile. Inside this break radius (r_b) characterize the logarithmic slope of the density profile as $\gamma = \frac{d \log I}{d \log r}$. Cusp: steep profile ($\gamma > 0.3$), Core: shallow profile ($\gamma < 0.3$).





Luminous ellipticals are typically core galaxies; cuspy galaxies are lower luminosity systems.

Significant overlap at intermediate luminosity.

Nuclei of elliptical galaxies: cusp/core profiles

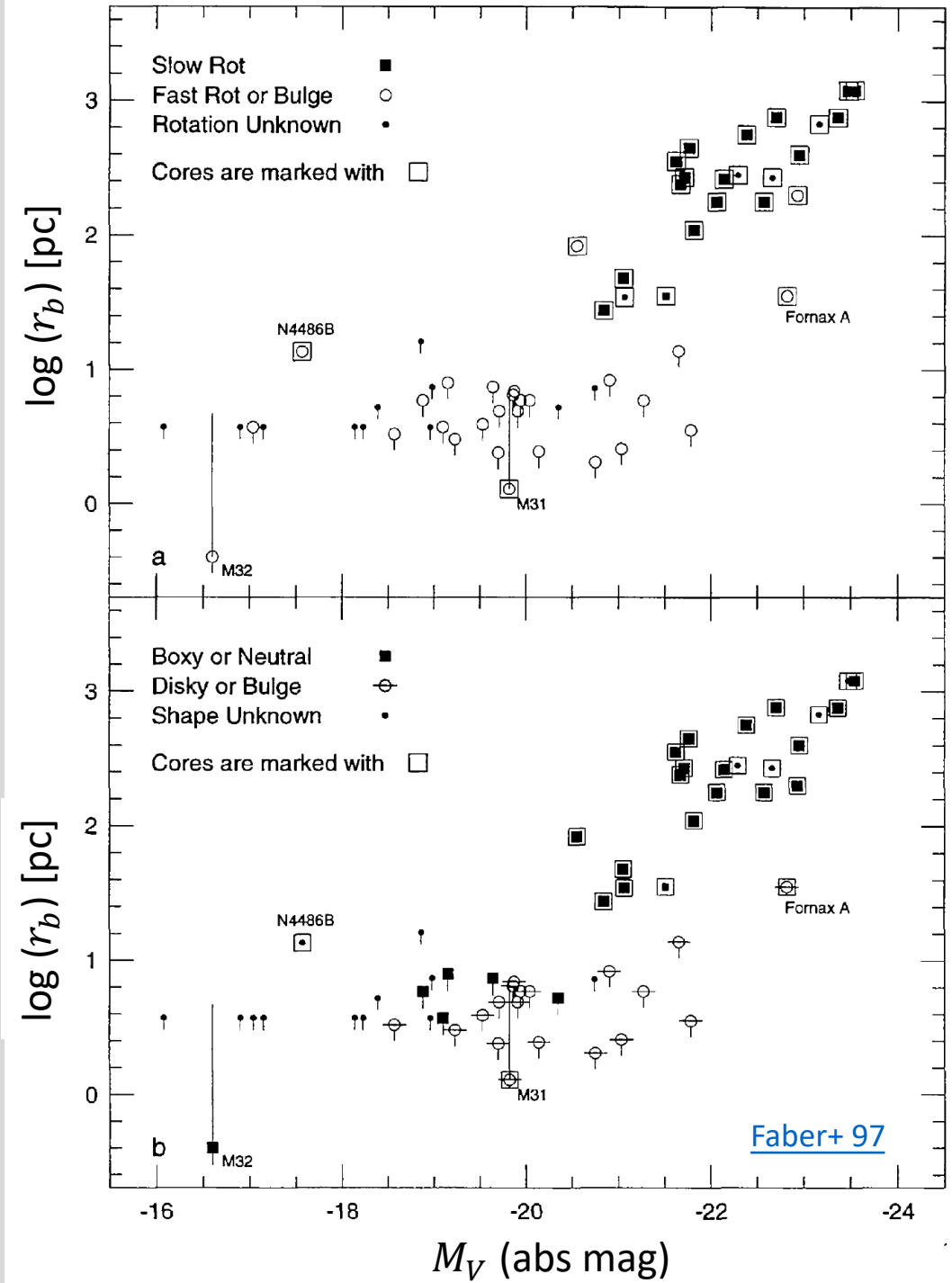
Cusp/core also correlates with other properties such as

- **Slow vs Fast Galaxy Rotation ⇒**

  ■ Slow rotators: big core radii, flat core profiles
  ○ Fast rotators: small or no core radii, cuspy profiles

- **Boxy vs Disky Galaxy Isophotes ⇒**

  ■ Boxy galaxies: big core radii, flat core profiles
  ⦶ Disky galaxies: small or no core radii, cuspy profiles



Faber+ 97

Elliptical galaxy dichotomy?

Most Massive Ellipticals	Moderate Mass Ellipticals
Very luminous ($M_V < -21.5$)	Lower luminosity ($M_V > -21.5$)
Cores	Cusps
Boxy	Disky
Slow Rotators	Fast(er) Rotators
High Sersic indices (n>4): large extended envelopes.	Lower Sersic indices (4-ish): very deVaucouleur-like.
Very old stellar pops	Slightly younger (but still old) stellar pops
Often in densest environments	Range of environments

Remember, these are all biggish ellipticals, not dwarf ellipticals, dwarf spheroidals etc.

Merger Trees

Way of showing accretion/assembly history of a galaxy:

- time runs vertically down
- size of trunk/branches show mass of object.
- branch/merge points: merger event.

A massive galaxy today ($t=t_0$) was in many smaller units at higher redshift.

Q: How does one define "formation time"?

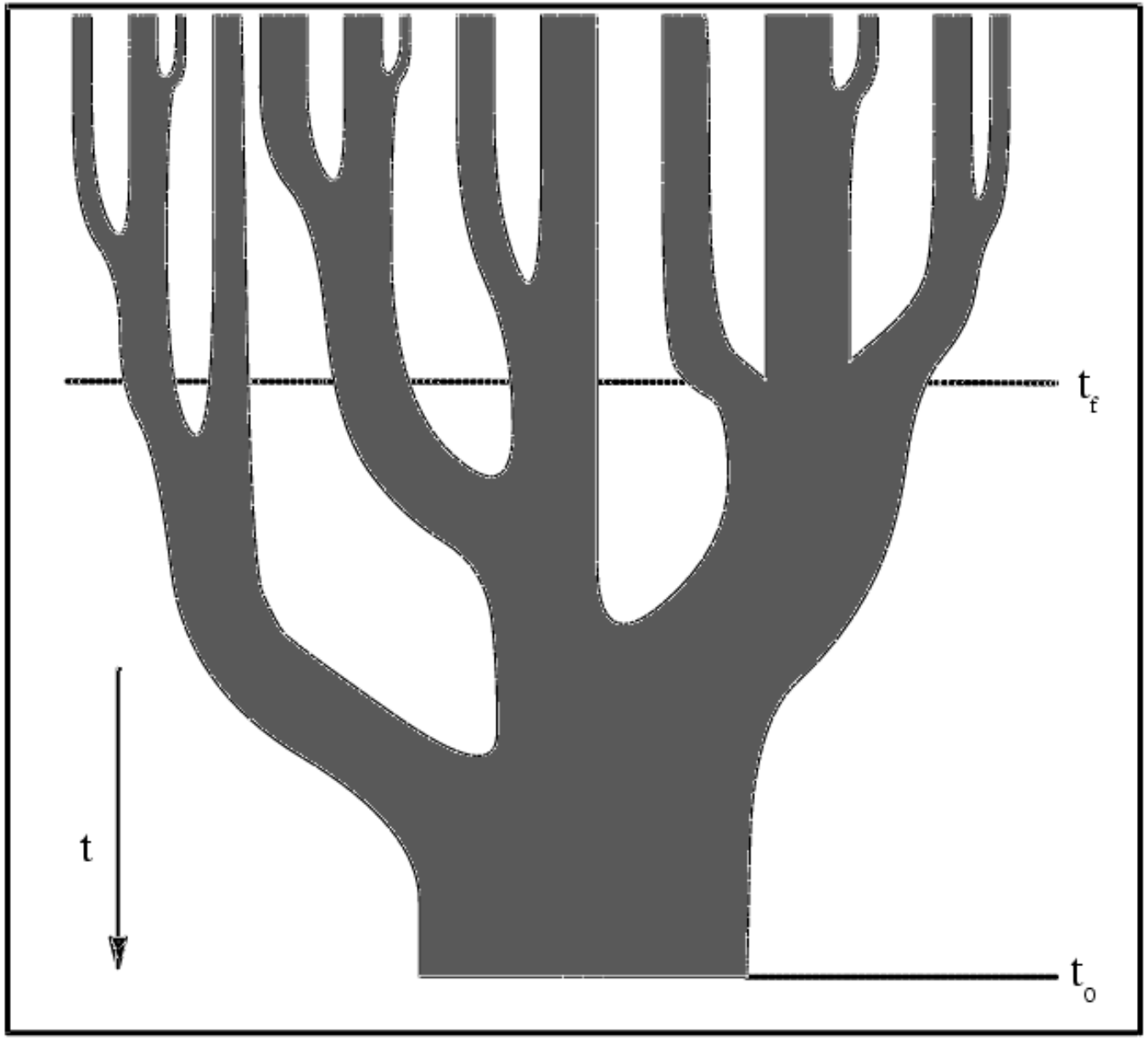
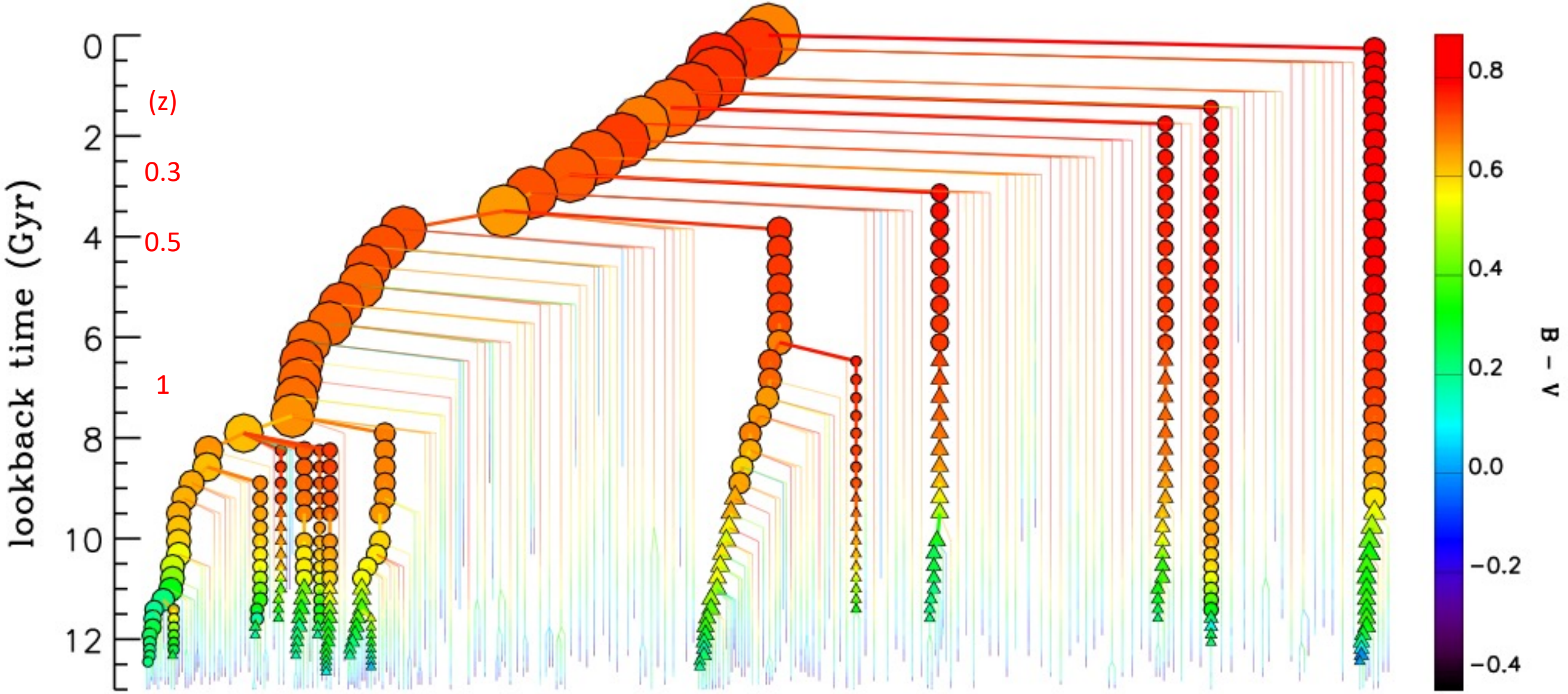


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

Merger tree for a massive cluster elliptical (cD)

Key:
Size of circle ⇒ stellar mass of objects
Color of circle ⇒ integrated color of stellar populations

de Lucia & Blazoit 07



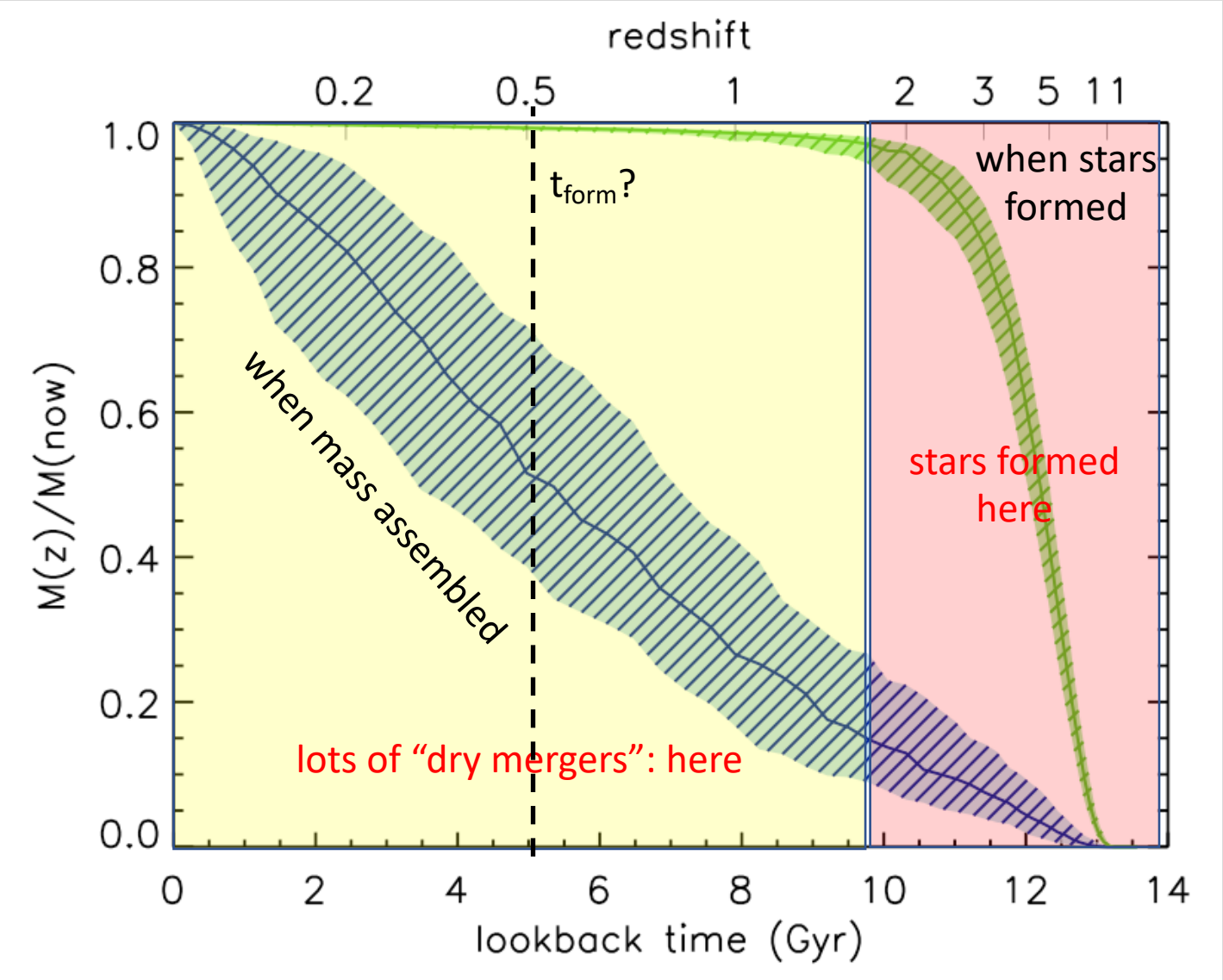
Star Formation History vs Assembly History

de Lucia & Blazoit 07

Look at the galaxy today. Two ways to think about the stellar mass:

1) star formation history: when did the stars actually form?

2) assembly history: what fraction of the stars were in a single object, as a function of time?



Characterizing Mergers

Wet vs dry:

- Wet merger: gas-rich galaxies, gas inflow, strong star formation, AGN
- Dry merger: gas-poor galaxies, only stars.

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Mass ratio:

- Major merger: galaxies have comparable mass
- Minor merger: one galaxy is much smaller

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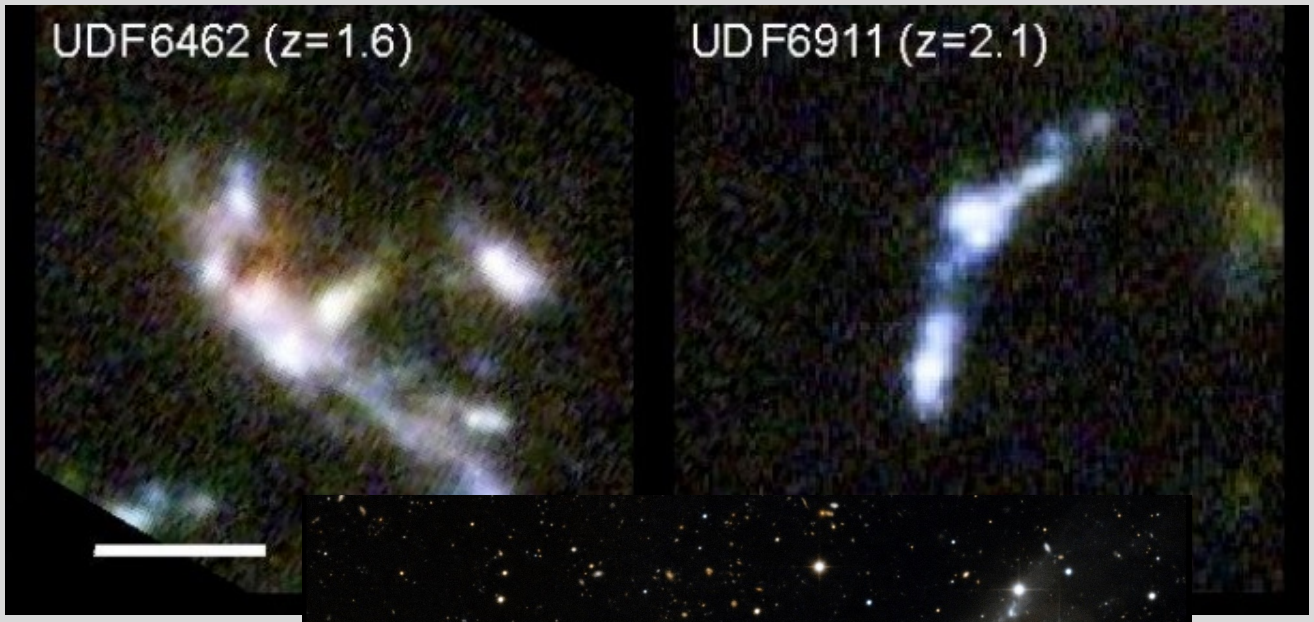
Timing of mergers:

- Early (high redshift)
- Late (low redshift)



Characterizing Mergers

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- Wet merger: gas-rich galaxies, gas inflow, strong star formation, AGN
- Dry merger: gas-poor galaxies, only stars.

Mass ratio:

- Major merger: galaxies have comparable mass
- Minor merger: one galaxy is much smaller

Timing of mergers:

- Early (high redshift)
- Late (low redshift)

Number of mergers

- One big one?
- Many smaller ones?

None of these are either/or possibilities, of course.....

Elliptical galaxy dichotomy?

Most Massive Ellipticals	Moderate Mass Ellipticals
Very luminous ($M_V < -21.5$)	Lower luminosity ($M_V > -21.5$)
Cores	Cusps
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Very old stellar pops	Slightly younger (but still old) stellar pops
Often in densest environments	Range of environments

Remember, these are all biggish ellipticals, not dwarf ellipticals, dwarf spheroidals etc.

General picture: the most massive mergers likely formed through many dry mergers over time, typically in dense clusters. Lower mass systems more likely to come from wet mergers (in groups and field?), maybe marked by only one or a few big mergers.